METHOD AND SYSTEM FOR MOVING TARGET DETECTION, AND VEHICLE INCORPORATING SAME

Abstract:
A method of sensing a moving target using a plurality of transceivers (4-1 - 4-M), each transceiver being configured to transmit PMCW transmit signals via a respective antenna and to receive via the antenna reflection signals following reflection from the target. The PMCW transmit signals are cyclic whereby, during each outer code cycle, a transmit signal is transmitted by each transceiver with a respective inner code. The method comprises, for each transceiver, for each outer code cycle including a current outer code cycle, transmitting first transmit signals embodying a first outer code and a first inner code and receiving corresponding first reflection signals, switching from the first outer code to a second outer code and during a second outer code cycle, subsequent to the current outer code cycle, transmitting second transmit signals embodying the second outer code and a second inner code and receiving corresponding second reflection signals. The method further comprises receiving the reflection signals for all transceivers including the...
first reflection signals and the second reflection signals. The received reflection signals are processed to determine the presence, range and/or dimensions of a target within a field of view of the antennas.
Method and system for moving target detection, and vehicle incorporating same

Technical field

[0001] The present invention generally relates to multiple input, multiple output, MIMO radar based object detection, in particular moving target detection using phase modulated continuous wave (PMCW) signals. The invention finds use in short range radar (SRR) systems, e.g. for use in an automotive applications. In embodiments, the present invention relates to a method and system for moving target detection, and to a vehicle incorporating same.

Background of the Invention

[0002] In order to gain a maximum information (e.g. through multiple input, multiple output, MIMO) about the scene around the vehicle, future automotive radar systems will operate with numerous devices (transceivers) spread over the vehicle and/or that are co-located. In order to be able to process different signals, a form of orthogonality of the different codes transmitted by the transceivers is necessary. This can for instance be achieved by switching on and off the particular devices (time multiplexing). The orthogonality in this case is simply guaranteed by the fact that exactly one code is propagating through the environment in some fixed time period. However, this method has some obvious drawbacks - the dwell time of the underlying processing increases and this increase scales in linear way with the number of transmitters. This means that the resulting information gives more and more coarse time snap shots of the scenarios as the number of devices increase. This bears the risk that important details are detected too late or are even missed.

[0003] Another possibility to achieve orthogonality is to choose orthogonal codes, for instance non-overlapping frequencies or orthogonal phase codes, for example where there is orthogonality by means of the so called outer coding in phase modulated continuous wave radar system (PMCW). The principle of the outer coding in PMCW can be explained by means of the binary phase modulated codes, the mathematical principles of which discussed in more detail herein below.
[0004] However, a problem is that this outer coding principle degenerates in the case of targets with high relative velocities. This issue can lead to ghost targets. That is, where an outer coding is used to achieve orthogonality between signals transmitted from different antennas, as this outer coding relies on cancellation of inner code signals during the accumulation phase, the orthogonality degenerates for echoes from targets with high relative velocity. This issue is in particular critical for certain outer code combinations, which might be unavoidable if the involved number of signals is large. This effect can lead to ghost targets.

[0005] EP 3 00491 8A1 discloses a radar system for transmitting a FMCW radar sensor signal encompassing a series of frequency modulation ramps and phase-modulated with a first code sequence orthogonal to a respective other code sequence with which a time-synchronized transmitted signal of another FMCW radar sensor is phase-modulated; the radar echoes are phase-demodulated with a code sequence correlating with the first code sequence; and a distance and/or a relative speed of a localized object is identified from a Fourier analysis frequency spectrum, in a first dimension over sampled radar echo values of a frequency modulation ramp, and in a second dimension over the phase-demodulated sequence of radar echoes of the ramps of the transmitted signal; and a vehicle fleet radar system having an FMCW radar sensor in which a code set satisfying a code set orthogonality condition with a code set of a radar sensor of another vehicle is used for phase modulation/demodulation.

Object of the invention

[0006] A problem addressed by the present invention is how to provide an effective moving target detection method and system that does not degenerate in case of targets with high relative velocities and/or generate ghost targets.

General Description of the Invention

[0007] In order to overcome the abovementioned problems, the present invention provides a method of sensing a moving target using a plurality of transceivers, each transceiver being configured to transmit PMCW transmit signals via a respective antenna and to receive via an antenna(s) reflection signals following reflection from the target, the PMCW transmit signals being cyclic whereby, during each outer code cycle, a transmit signal is transmitted by each transceiver with a
respective inner code, the method comprising: for each transceiver, for each outer
code cycle including a current outer code cycle, transmitting first transmit signals
embodying a first outer code and a first inner code and receiving corresponding
first reflection signals; switching from the first outer code to a second outer code;
and during a second outer code cycle, subsequent to the current outer code cycle,
transmitting second transmit signals embodying the second outer code and a
second inner code and receiving corresponding second reflection signals;
receiving the reflection signals for all transceivers including the first reflection
signals and the second reflection signals; and processing the received reflection
signals to determine the presence, range and/or dimensions of a target within a
field of view of the antennas.

[0008] Preferably, for a first transceiver and a second transceiver that are co-
located or quasi co-located in units of a predetermined range resolution for the
method, a shifted inner code used during operation of the second transceiver is
mutually shifted with respect to an unshifted inner code used during operation of
the first transceiver. Preferably, generation of the shifted inner code implemented
by a systematic mutual time delay of the transmitted inner codes for transceivers
that are quasi at the same location. Preferably, the shifted inner code is given by
\[ G_k(l) = IC(\text{mod}(l + k, L)) \] , where \( IC \) is the unshifted inner code and \( L \) is the length
of the inner code \( IC \).

[0009] Preferably, the plurality of transceivers comprises \( M \) transmitters
\( TX_1, \ldots, TX_M \) and the outer codes \( OC_1, \ldots, OC_M \) each have length \( M \).

[0010] Preferably, switching, for each transceiver, from the first outer code to a
second outer code comprises switching the outer code that is transmitted by the
single transceiver \( TX_j \), \( j = 1, \ldots, M \) in a way such that no two transceivers operate
with the same outer code in one outer code cycle.

[0011] In one embodiment, switching, for each transceiver, from the first outer
code to a second outer code comprises switching the outer code according to a
predetermined protocol.

[0012] In another embodiment, switching, for each transceiver, from the first outer
code to a second outer code comprises randomly switching the outer codes.
[0013] In one embodiment, the first inner code and the second inner code are the same.

[0014] In another embodiment, the first inner code and the second inner code are different.

[0015] In one embodiment, the inner codes for all transceivers are different.

[0016] In one embodiment, the PMCW transmit signals transmitted by the plurality of transceivers are multiplexed.

[0017] According to another aspect of the invention, there is provided a detection system for sensing a moving target, the system comprising: a plurality of transceivers, each transceiver being configured to transmit PMCW transmit signals via a respective antenna and to receive via the antenna reflection signals following reflection from the target, the PMCW transmit signals being cyclic whereby, during each outer code cycle, a transmit signal is transmitted by each transceiver with a respective inner code; and processing circuitry, the processing circuitry being coupled to each of the transceivers and being configured to perform the method of any of claims 1 to 12 of the appended claims, or according to any of the particular embodiments described herein.

[0018] According to another aspect of the invention, there is provided a vehicle comprising a detection system with a plurality of transceivers, each transceiver being configured to transmit PMCW transmit signals via a respective antenna and to receive via the antenna reflection signals following reflection from the target, the PMCW transmit signals being cyclic whereby, during each outer code cycle, a transmit signal is transmitted by each transceiver with a respective inner code; and processing circuitry, the processing circuitry being coupled to each of the transceivers and being configured to perform the method according to any of the embodiments described above.

[0019] In one embodiment, considering for instance the family of Walsh-Hadamard codes, one observes that the most outer code combinations (encoding-decoding sequence pair) are uncritical in a sense that orthogonality is robust towards targets with high relative velocity. However, the critical combinations are not avoidable as soon as the number of signals has a certain quantity (about >15). But overall, that the average orthogonality for the codes is good. The present
invention operates to benefit from the good average properties by switching the outer code in a systematic or random way after each outer coding cycle. In addition, for the case of co-located devises it is proposed to introduce a mutual shift of the inner codes which is necessary to make the latter method work for this case (in other words, a mutual distance is mimicked).

[0020] In embodiments, the outer codes are mutually switched between the different transmitters. In this way the average orthogonality (ghost target cancellation) over all codes can be achieved. The average orthogonality might be much better than in the severe cases.

[0021] In embodiments, in order to mimic a mutual distance of co-located transmitters, a delay of the inner codes is used. The mutual distance is necessary to achieve the average orthogonality by switching outer codes.

[0022] Advantages of the invention, at least in embodiments, include the following: robust orthogonality towards Doppler shift in large MIMO radar systems; systematic or random switching of outer codes; and Mutual delay of inner coding - mimic distance for transmitters that are collocated.

Brief Description of the Drawings

[0023] Further details and advantages of the present invention will be apparent from the following detailed description of not limiting embodiments with reference to the attached drawing, wherein:

Figure 1 illustrates a fast time code with M accumulations, equal to outer code (OC) length, according to known outer coding techniques;

Figure 2 graphically represents the transmitted fast time codes for M transmitters, according to known outer coding techniques;

Figures 3 to 5 show histograms of n(j, k) for Walsh-Hadamard code length 32, 64 and 128, according to known outer coding techniques;

Figure 6 is a schematic diagram of a detection system 2 for sensing a moving target, according to an embodiment of the invention.

Figure 7 illustrates techniques for switching of outer codes after each outer code cycle (fast time processing) according to embodiments of the invention;
Figure 8 is a flow chart illustrating the generation of code(s) at some algorithm iteration \( k \) at some Tx/Rx device (i.e., some channel 4-y), using a fixed inner code;

Figure 9 is a flow chart illustrating the generation of code(s) at some algorithm iteration \( k \) at some Tx/Rx device (i.e., some channel 4-y), using a non-fixed inner code;

Figure 10 is a flow chart illustrating the generation of code(s) at some algorithm iteration \( k \) at some Tx/Rx device (i.e., some channel 4-y), using a fixed and delayed inner code; and

Figures 11 to 17 show plots of amplitude vs range (PMCW distance plot) for various code lengths, coding configurations and switching methods, including techniques according to embodiments of the invention.

**Description of Preferred Embodiments**

[0027] In the following, like numerals will be used to indicate like elements.

1. **Introduction**

[0028] While the present invention is described in the context of automotive applications, the techniques described herein can be applied in any sensing system to detect moving targets, that transmits and receives certain signals that have a phase and that consists of several input/output channels.

2. **Mathematical principles**

[0029] In this section, the mathematical principles underlying the present invention will be described.

[0030] Figure 1 illustrates a fast time code with \( M \) accumulations, here equal to outer code (OC) length. Let \( I_C \) be the binary inner code of length \( L \), i.e. the code applied for range detection by means of correlation, and \( OC_1, \ldots, OC_M \) mutually orthogonal binary outer codes of length \( M \). Then the fast time processing can be represented graphically as shown in Fig. 1.

[0031] In the same way, for \( M \) transmitters, the transmitted fast time codes can be graphically represented as shown in Fig. 2.
[0032] The signal transmitted with outer code $OC_j$ and with a delay $\tau_1$ that results in range bin corresponding to delay $\tau_2$ is written

$$D(j, \tau_1, \tau_2) = \sum_{l=1}^{M} \text{corr}(IC \cdot OC_j(l), \tau_1, \tau_2) \cdot OC_j(l) = \sum_{l=1}^{M} \text{corr}(IC, \tau_1, \tau_2) \cdot (OC_j(l))^2$$

[0033] When the same signal is decoded with respect to a general outer code $OC_k$ then

$$D(j, k, \tau_1, \tau_2) = \sum_{l=1}^{M} \text{corr}(IC, \tau_1, \tau_2) \cdot OC_k(l) \cdot OC_j(l)$$

(Equation 1: Decoded fast time signal, static targets).

[0034] Here $\text{corr}(c, \tau_1, \tau_2)$ denotes the autocorrelation of a code $c$ delayed (and circular shifted) by $\tau_1$ and $\tau_2$, respectively. In case that $\tau_1 \neq \tau_2$ the inner code gives $\text{corr}(JC, \tau_1, \tau_2) \approx 0$ under the assumption of good autocorrelation properties, and this yields $D(J, k, \tau_1, \tau_2) \approx 0$. In case $\tau_1 = \tau_2$ but $k \neq j$ the orthogonality $OC_k$ and $OC_j$ gives $D(j, k, \tau_1, \tau_2) \approx 0$. Therefore, as desired, $D(j, k, \tau_1, \tau_2)$ gives a significant peak only for $j = k, \tau_1 = \tau_2$.

[0035] However, the given reasoning only holds with limitations in case of moving targets. In this case, the Doppler phase shift has to be included in Equation 1. For a target with relative velocity $v$ the fast time decoding results can be estimated as follows

$$D(j, k, \tau_1, \tau_2, v) \approx \sum_{l=1}^{M} \text{corrQC}(c, \tau_1, \tau_2) \cdot OC_k(l) \cdot OC_j(l) \cdot \exp\left(4\pi i L c(L) \frac{v}{\lambda}\right)$$

(Equation 2: Decoded fast time signal, moving targets included.)

where $\lambda$ is the wavelength and $L$ is the inner code length with corresponding chip duration $c(L)$.

[0036] For $j \neq k, \tau_1 = \tau_2$ the orthogonality of the outer code degenerates with increasing velocity. This effect is most critical for long experts of the outer codes where $OC_k(l) \cdot OC_j(l)$ has constant sign, for instance $OC_k = [1 \ldots 1, -1 \ldots -1]$, $OC_j = [1 1 \ldots 1]$. In these cases, the phase shift is most significant, provided it did not trace out the full circle. For Walsh-Hadamard codes, the most severe cases
occur for instance in the decoding $D\left(1,\frac{M}{2} + 1,\tau,\tau, v\right)$ for large $v$ since $C_1 = 1$, $OCM_{\frac{M}{2}+1}(l) = 1$ for $l \leq \frac{M}{2}$ and $OCM_{\frac{M}{2}+1}(7) = -1$ for $l > \frac{M}{2}$.

[0037] For Walsh-Hadamard outer coding of length $M$ the following cancellation, compared to ideal decoding, applies in the most severe combination of outer codes:

$$q(v, L, \frac{M}{\lambda}) := 20 \cdot \log_{10} \left| 1 - \exp \left(4\pi i \frac{v}{\lambda} l c(L)\right) \cdot \frac{1}{2} \right|$$

in dB (power).

[0038] In general, for encoding with $OC_k$ and decoding with $OC_j$ the maximum length of constant sign of $OC_k(l) \cdot OC_j(l)$ defines a crucial parameter. In fact, it is not the maximum length of constant sign but the following closely related parameter:

$$n(j, k) \equiv \max_{l \in \{1, \ldots, m\}} \min_{h \in \{1, \ldots, m\}} (|l - h| \cdot OC_j(Z) \cdot OC_k(l) \neq OC_j(h) \cdot OC_k(h))$$

{Equation 3: Crucial parameter for cancellation loss for two outer codes}.

[0039] The cancellation (in dB (power)) compared to ideal decoding then can be assessed by:

$$q(v, L, n(j, k)) := 20 \cdot \log_{10} \left| 1 - \exp \left(4\pi i \frac{v}{\lambda} n(j, k) l c(L)\right) \cdot \frac{1}{2} \right|$$

{Equation 4: Cancellation by outer coding with respect to ideal decoding}.

3. Quantitative figures for outer coding target suppression

[0040] In this section, quantitative values for the cancellation $= q(v, L, n(j, k))$ in Equation 4 are given. Further, the crucial parameter $n(j, k)$ for Walsh-Hadamard codes of certain length is given.
Table 1 shows that, in the worst case outer code combination, the target cancellation is not sufficient for long outer coding sequences and higher velocities.

The inventors have discovered that the critical parameter is \( n(j, k) \) (Equation 3), and hence the outer coding performance overall sequences depends on the distribution of this parameter.

Figures 3 to 5 show histograms of \( n(j, k) \) for Walsh-Hadamard code length 32, 64 and 128. The histograms of Figs 3 to 5 show that the number of critical sequences from the perspective of a fixed decoding sequence is actually very low, even for Walsh-Hadamard codes of length 64 and 128.

The inventors have discovered that, due to the structure of the Walsh-Hadamard codes, the distribution of \( n(1,k), \ldots, n(M,k) \) is equal for all \( k = 1, \ldots, M \).

The average code length of constant sign is, in accordance with the histograms of Figs 3 to 5, very low (2.5, 3, 3.5 for Walsh-Hadamard code length 32, 64, 128 respectively). The average cancellation is hence significantly better compared to the worst case (c.f. Table 1. Cancellation for \( L=1000 \) code length, chip duration \( c(L) = 0.5 \) ns and most critical combination of Walsh-Hadamard outer codes with the specified outer code length).
codes with the specified outer code length) as shown in the following table (Table 2):

<table>
<thead>
<tr>
<th>'velocity [m/s]'</th>
<th>Length Hadamard outer code</th>
<th>'cancellation dB'</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>32</td>
<td>-39.71462882</td>
</tr>
<tr>
<td>10</td>
<td>32</td>
<td>-33.69449272</td>
</tr>
<tr>
<td>15</td>
<td>32</td>
<td>-30.17344059</td>
</tr>
<tr>
<td>20</td>
<td>32</td>
<td>-27.67547817</td>
</tr>
<tr>
<td>30</td>
<td>32</td>
<td>-24.1570156</td>
</tr>
<tr>
<td>40</td>
<td>32</td>
<td>-21.66257127</td>
</tr>
<tr>
<td>5</td>
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<td>-38.13107193</td>
</tr>
<tr>
<td>10</td>
<td>64</td>
<td>-32.11113991</td>
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<tr>
<td>10</td>
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</tr>
<tr>
<td>40</td>
<td>128</td>
<td>-18.74951573</td>
</tr>
</tbody>
</table>

Table 2: Average cancellation for L=1000 code length, chip duration c(L)=0.5 ns. Average taken over all available Walsh-Hadamard codes of the respective length.

4. Improving cancellation by switching outer codes

[0046] Figure 6 is a schematic diagram of a detection system 2 for sensing a moving target, according to an embodiment of the invention. It will be appreciated that such system may be implemented using conventional computing machinery, incorporating components such as processing circuitry, volatile and non-volatile memory, clocks, oscillators, and interfaces, as well as suitable software (modules) executing the algorithms described herein, as is known to persons skilled in the art. Where appropriate, elements in Fig. 6 are implemented using such components, and certain elements/components are omitted, for the purpose of illustration.

[0047] The detection system 2 is a MIMO system comprising a plurality (1, 2…M) of channels, collectively designated 4, of which a first channel 4-1 and a last channel 4-M are shown. On channel 4-1, a first inner code generator 6-1 receives at a first IC input 8-1 a first base signal and applies to it an inner code (used for ranging) to produce a first intermediate signal; and the latter is received at a first
OC input 10-1 of an outer code generator 12-1 and an outer code applied to the
first intermediate signal to produce a transmit signal that is transmitted via first
transmitter 14-1.

[0048] First receive signals (i.e. RF signals, including components reflected from
a target object) are received at first receiver 16-1 and supplied to a first inner code
correlator 18-1 which performs a first IC correlation operation to generate a first
inner code correlated signal; and the latter is output on a first IC output 20-1 and
received by a first outer code correlator 22-1, where a first OC correlation
operation is performed to generate a first correlated output signal at first OC output
24-1.

[0049] On each further channel 4, corresponding generators, transmitters and
receivers are used on corresponding, base, intermediate, transmit and receive
signals. Thus, finally, on channel 4-M, the corresponding elements are arranged
and function per the preceding two paragraphs, with the designator "-1" replaced
for the corresponding element by "-M".

[0050] The histograms in Figs 3 to 5 suggest that it should be possible to find
enough sequences that guarantee a good mutual cancellation for a fixed decoding
sequence. However, one has to take into account that the critical sequences are
different for different outer codes applied for decoding. In other words, the peaks
of \( n(j, k), n(l, k) \) as a function of \( k \) have different locations for \( j \neq l \).

[0051] The inventors have discovered that it is however possible to benefit from
the good cancellation properties in the average (c.f. Table 2). In one embodiment,
the approach is to mutually switch the outer codes after each fast time processing,
or after each outer code cycle.

[0052] Figure 7 illustrates techniques for switching of outer codes after each
outer code cycle (fast time processing) according to embodiments of the invention.

[0053] In the embodiment of Fig. 7, \( k(j, l) \in \{1, \ldots, M\} \) have to be chosen in a way
that \( k(j_1, i_1) \neq k(j_2, i_2) \).\(^{\text{anc}} \) \( i_1 = i_2 \), \( A = j_2 \) and \( i_1 \neq i_2 \). However, in
alternative embodiments, it is ensured that only one transmitter operates with the
same outer code in a fixed outer coding cycle.

[0054] In embodiments, this mitigation technique can however only work if the
transmitters have a certain mutual distance (about range bin length). This is clear
from the following consideration: if all transmitters are at quasi the same location, the receiver will see a large ghost target in each fast time step, each of which might be implied by signals transmitted from different transmitters but occur at the same location. In this way, these large ghost targets will also appear in the final range Doppler plane. The inventors have discovered that this issue can be overcome by implementing a systematic mutual time delay of the transmitted inner codes for transmitters that are quasi at the same location. In this way, the ghost targets arising in the different fast time steps will not be located in the same range bin and hence will be suppressed in the final range Doppler plane. In other words, this technique mimics a mutual distance between the transmitters.

[0055] According to embodiments of the invention, an algorithm implementing the invention can be summarised as follows.

[0056] Assuming a system operating with $M$ transmitters $TX_1, ..., TX_M$ and outer codes $OC_1, ..., OC_M$ each of which as length $M$. It is further assumed that all transmitters use the same inner code $IC$. (In the present disclosure, where the context requires, the terms "transmitter" and "transceiver" are used interchangeably.)

[0057] After each outer coding cycle (inner code is transmitted $M$ times) change the outer code that is transmitted by the single $TX_j, j = 1, ..., M$ in a way that no two transmitter apply the same outer code in one outer code cycle.

[0058] In addition, for the transmitters that are located at quasi the same place (in units of range resolution of the system) the corresponding transmitters operate with mutually shifted inner codes $C_k$, defined by $IC_k(1) = IC(mod(l + k, L))$ with $L$ the length of the inner code $IC$.

[0059] Figure 8 is a flow chart illustrating the generation of code(s) at some algorithm iteration $k$ at some Tx/Rx device (i.e. some channel $4-j$) using a fixed inner code. Received as inputs are a (base) RF signal 82 and, in this embodiment, a fixed inner code 84. At step s2, the received inner code $IC_j$ is applied to the (base) RF signal 82, e.g. at a respective inner code generator $6-j$ (see Fig. 6). Then (step s4), it is determined whether an outer code cycle has finished, i.e. a new outer code cycle is being entered. If so, a new outer code is set at step s6, thus providing current outer code $OC(J, k)$ 86; and the latter is supplied as input to
the subsequent step (s8) at which the current outer code \( OC(J, k) \) is applied to the signal. Steps s4 to s8 may be performed, for example, at a respective outer code generator 12-y. Thereafter, the derived encoded signal (transmit signal) is transmitted by respective transmitter 14-y at step s10.

[0060] Figure 9 is a flow chart illustrating the generation of code(s) at some algorithm iteration \( k \) at some Tx/Rx device (i.e. some channel 4-y), using a non-fixed inner code. At step s1, e.g. at a respective outer code generator 12-y, a new outer code \( OC(J, k) \) is set. This causes, e.g. at a respective inner code generator 6-y (see Fig. 6), the updating of the inner code to produce a current inner code \( (IC(j)) 84' \).

[0061] Received as inputs are a (base) RF signal 82 and, in this embodiment, the current inner code \( (IC(/)) 84' \). At step s2, the received current inner code \( (IC(/)) 84' \) is applied to the (base) RF signal 82, e.g. at a respective inner code generator 6-y (see Fig. 6). Then (step s4), it is determined whether an outer code cycle has finished, i.e. a new outer code cycle is being entered. If so, a new outer code is set at step s6, thus providing current outer code \( OC(J, k) 86 \); and the latter is supplied as input to the subsequent step (s8) at which the current outer code \( OC(J, k) \) is applied to the signal. Steps s4 to s8 may be performed, for example, at a respective outer code generator 12-y. Thereafter, the derived encoded signal (transmit signal) is transmitted by respective transmitter 14-y at step s10.

[0062] Figure 10 is a flow chart illustrating the generation of code(s) at some algorithm iteration \( k \) at some Tx/Rx device (i.e. some channel 4-y), using a fixed and delayed inner code. Received as inputs are a (base) RF signal 82 and, in this embodiment, a fixed inner code 84. At step s2, the received inner code \( IC/j \) is applied to the (base) RF signal 82, e.g. at a respective inner code generator 6-y (see Fig. 6).

[0063] Next, at step s3, a fixed delay \( \tau (j) 85 \) is received as input and applied, e.g. at the respective inner code generator 6-y, to an intermediate signal resulting from the application of the inner code \( IC/j \) to the (base) RF signal 82.

[0064] Then (step s4), it is determined whether an outer code cycle has finished, i.e. a new outer code cycle is being entered. If so, a new outer code is set at step s6, thus providing current outer code \( OC(J, k) 86 \); and the latter is supplied as input
to the subsequent step (s8) at which the current outer code \( OC(J, k) \) is applied to the signal. Steps s4 to s8 may be performed, for example, at a respective outer code generator 12-\( j \). Thereafter, the derived encoded signal (transmit signal) is transmitted by respective transmitter 14-\( j \) at step s10.

[0065] It will be appreciated by persons skilled in the art that the above assumptions/configurations regarding the number of transmitters (transceivers), code lengths, etc. may be diverged from, where appropriate.

[0066] The techniques according to embodiments of the invention can be applied in various ways. For example, the code switching may be combined with time multiplexing of the transmitted transceiver signals. Such combining of the above method with methods like time-multiplexing may be useful in very large MIMO settings (many Tx/Rx devices). However, in that case, the techniques according to embodiments of the invention may not be sufficient to suppress the spillover, at least to the same extent. The implementation may be as follows: the entirety of Tx/Rx devices are divided into several sub-packages that operate at distinct times, each of which applies the techniques according to embodiments of the invention of switching inner codes.

[0067] Alternatively or additionally, the aforementioned techniques may be combined with different inner coding. The use of different inner codes can be beneficial for the same reason and the potential implementation may be as follows: the entirety of Tx/Rx devices are divided into several sub-packages that operate with different inner codes, where each package applies the proposed approach to switch inner codes.

[0068] The efficiency of the techniques according to embodiments of the invention is demonstrated by simulations discussed in the following section ("Simulation results").

5. Simulation results

[0069] The simulation results set out below show how the technique described in the previous section work in a simple setting, for the purpose of illustration.

[0070] The following simplifications have been applied in the inventors' simulations:

- Very low spillover: -100 dB
- Low noise figure: 0 dB.

[0071] For Walsh-Hadamard codes the following notion is applied: The Walsh-Hadamard code in the k-th row of the Walsh-Hadamard matrix of size n x n is denoted by H(n,k).

[0072] Simulation setup: The system is located at the origin. The decoding of the range plots shown in the Figures is carried out with respect to outer code constantly equal 1 (first Walsh-Hadamard code).

[0073] The target configuration is illustrated in the following table (Table 3):

<table>
<thead>
<tr>
<th>Target ID</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Position</td>
<td>[5;0;0]</td>
<td>[10;0;0]</td>
<td>[15;0;0]</td>
</tr>
<tr>
<td>Velocity m/s</td>
<td>10</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3 Target configuration

[0074] Figures 7 to 13 show plots of amplitude vs range (PMCW distance plot) for various code lengths, coding configurations and switching methods.

[0075] Figure 7 illustrates the usual setting - decoding and encoding with same outer code, Walsh-Hadamard code length 128.

[0076] Figure 8 illustrates the worst case - decoding with H(128,1) and encoding with H(128,65).

[0077] However, the application of the outer code switching in accordance with embodiments of the invention can significantly improve the cancellation:

[0078] Figure 9 illustrates decoding with H(128,1) and switching outer codes in encoding. The above simulation results (Figs 7 to 9) show the results when only one transmitter is active; hence only the average cancellation for one transmitter is demonstrated therein. The interplay of different transmitters also with mutually time delay of the transmitted code, as it is described in the previous section, is shown in the subsequent figures for the case of Walsh-Hadamard outer codes of length 32.

[0079] The first two simulations (Fig. 1 and 11) show the case of usual decoding with only one system and the most critical loss of cancellation for one system operating with a critical outer code and without any mitigation technique.
The target configuration in the following simulations are given in Table 4:

<table>
<thead>
<tr>
<th>TargetID</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitialPosition</td>
<td>[5;0;0]</td>
<td>[10;0;0]</td>
<td>[15;0;0]</td>
</tr>
<tr>
<td>Velocity m/s</td>
<td>40</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

In Fig. 1, the system is located at the origin. The decoding of the range plots shown is carried out with respect to an outer code constantly equal to 1. Only own signal (→ 1-1(32,1)) is transmitted.

In Fig. 2, the system is located at the origin. The decoding of the range plots shown is carried out with respect to an outer code constantly equal to 1 (1-1(32,1)). Only the signal with outer coding 1-1(32,17) is transmitted, leading to ghost targets due to loss in cancellation.

In the following embodiment, simulation in the case of 31 transmitters located at one place (here, the origin) is considered. All systems operate with different outer codes (H(32,2)...H(32,32)) orthogonal to the decoding outer code (1-1(32,1)). Hence, in the ideal scenario, no target would be visible. In the first simulation (Figure 12), only the outer codes are mutually changed, while in the second plot (Fig. 4, Fig. 3) the mutual time delay (shifted inner code) is also applied.

In Fig. 3, thirty-one (31) systems (transceivers) are located at the origin, each operating with different but changing (after 32 accumulations) outer codes (H(32,2)...H(32,32)). Decoding is done with 1-1(32,1). It is noted that there is no mutual delay in inner codes, meaning that average cancellation does not work optimally.

In Fig. 4, thirty-one (31) systems (transceivers) are located at the origin, each operating with different but changing (after 32 accumulations) outer codes (H(32,2)...H(32,32)). Decoding is done with 1-1(32,1). There is a mutual delay in inner codes (5 range bins), leading to average cancellation being kept even with same location of all transmitters.

**Conclusion**

The loss of cancellation (degenerated orthogonality) implied by moving targets in outer coding of the PMCW system has been investigated by the
inventors. It is quantified that in the severe scenarios of long outer codes and fast moving targets the cancellation is seriously corrupted (c.f. Table 1. Cancellation for \(L=1000\) code length, chip duration \(c(L) = 0.5\) ns and most critical combination of Walsh-Hadamard outer codes with the specified outer code length). However, the number of critical outer codes from the perspective of a fixed outer code is very low. Therefore, the average cancellation is much better, c.f. Table 2: Average cancellation for \(L=1000\) code length, chip duration \(c(L)=0.5\) ns. Average taken over all available Walsh-Hadamard codes of the respective length. The inventors have established that that leaving out particular outer codes will not solve the cancellation issue since the critical outer codes are different for different outer codes applied in decoding. Furthermore the technique to achieve the average cancellation in Table 2: Average cancellation for \(L=1000\) code length, chip duration \(c(L)=0.5\) ns. Average taken over all available Walsh-Hadamard codes of the respective length devised by the inventors has been set out. In embodiments, this technique consists of a mutual switch of the applied outer codes and, in an embodiment, a mutual delay of the transmitted inner code (in order to mimic a distance for transmitters at the same location). The results confirm that this method is effective, e.g. in the inventor's simulation framework.
Claims

1. A method of sensing a moving target using a plurality of transceivers, each transceiver being configured to transmit PMCW transmit signals via a respective antenna and to receive via an antenna reflection signals following reflection from the target, the PMCW transmit signals being cyclic whereby, during each outer code cycle, a transmit signal is transmitted by each transceiver with a respective inner code, the method comprising: for each transceiver, for each outer code cycle including a current outer code cycle, transmitting first transmit signals embodying a first outer code and a first inner code and receiving corresponding first reflection signals; and switching from the first outer code to a second outer code; during a second outer code cycle, subsequent to the current outer code cycle, transmitting second transmit signals embodying the second outer code and a second inner code and receiving corresponding second reflection signals; receiving the reflection signals for all transceivers including the first reflection signals and the second reflection signals; processing the received reflection signals to determine the presence, range and/or dimensions of a target within a field of view of the antennas.

2. The method according to claim 1, wherein for a first transceiver and a second transceiver that are co-located or quasi co-located in units of a predetermined range resolution for the method, a shifted inner code used during operation of the second transceiver is mutually shifted with respect to an unshifted inner code used during operation of the first transceiver.

3. The method according to claim 2, wherein generation of the shifted inner code implemented by a systematic mutual time delay of the transmitted inner codes for transceivers that are quasi at the same location.

4. The method according to claim 1, 2 or 3, wherein the shifted inner code is given by $C_k(l) = IC(mod(l + k, L))$, where $IC$ is the unshifted inner code and $L$ is the length of the inner code $IC$. 
5. The method according to claim 1 to 4, wherein the plurality of transceivers comprises \( M \) transmitters \( TX_1, \ldots, TX_M \) and the outer codes \( OC_1, \ldots, OC_M \) each have length \( M \).

6. The method according to any of the preceding claims, wherein switching, for each transceiver, from the first outer code to a second outer code comprises switching the outer code that is transmitted by the single transceiver \( TX_j, j = 1, \ldots, M \) in a way such that no two transceivers operate with the same outer code in one outer code cycle.

7. The method according to any of the preceding claims, wherein wherein switching, for each transceiver, from the first outer code to a second outer code comprises switching the outer code according to a predetermined protocol.

8. The method according to any of the preceding claims, wherein wherein switching, for each transceiver, from the first outer code to a second outer code comprises randomly switching the outer codes.

9. The method according any of the preceding claims, wherein the first inner code and the second inner code are the same.

10. The method according to any of the preceding claims, wherein the first inner code and the second inner code are different.

11. The method according to claim 9, wherein the inner codes for all transceivers are different.

12. The method system according to any of the preceding claims, wherein the PMCW transmit signals transmitted by the plurality of transceivers are multiplexed.

13. A detection system for sensing a moving target, the system comprising:

   a plurality of transceivers, each transceiver being configured to transmit PMCW transmit signals via a respective antenna and to receive via the antenna reflection signals following reflection from the target, the PMCW transmit signals being cyclic whereby, during each outer code cycle, a transmit signal is transmitted by each transceiver with a respective inner code; and
processing circuitry, the processing circuitry being coupled to each of the transceivers and being configured to perform the method of any of the preceding claims.

14. A vehicle comprising a detection system according to claim 13.
Fig. 6

<table>
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<tr>
<th>TX_1</th>
<th>OC_{k(1,1)}(1)</th>
<th>...</th>
<th>OC_{k(1,1)}(M)</th>
<th>OC_{k(1,1)}(1)</th>
<th>...</th>
<th>OC_{k(1,1)}(M)</th>
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<tr>
<td>TX_2</td>
<td>OC_{k(2,1)}(1)</td>
<td>...</td>
<td>OC_{k(2,1)}(M)</td>
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<td></td>
<td>...</td>
<td></td>
<td>...</td>
<td>...</td>
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<tr>
<td>TX_M</td>
<td>OC_{k(M,1)}(1)</td>
<td>...</td>
<td>OC_{k(M,1)}(M)</td>
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<td>...</td>
<td>OC_{k(M,1)}(M)</td>
</tr>
</tbody>
</table>

1st outer code cycle

i-th outer code cycle

Slow time processing

Fig. 7

SUBSTITUTE SHEET (RULE 26)
Generation of code at some algorithm iteration \( k \) at some Tx/Rx device \( j \)

- \( s2 \): Apply IC \( (j) \)
- \( s4 \): If new outer coding cycle
  - Set new OC \( (j, k) \)
  - Current outer code OC \( (j, k) \)
- \( s8 \): Apply OC \( (j, k) \)
- \( s10 \): Transmit

**Fig. 8**

Generation of code at some algorithm iteration \( k \) at some Tx/Rx device \( j \), non fixed inner code

- \( s1 \): Set new OC \( (j, k) \)
- \( s2 \): Apply IC \( (j) \)
- \( s4 \): If new outer coding cycle
  - Set new OC \( (j, k) \)
  - Current outer code OC \( (j, k) \)
- \( s8 \): Apply OC \( (j, k) \)
- \( s10 \): Transmit

**Fig. 9**

SUBSTITUTE SHEET (RULE 26)
Generation of code at some algorithm iteration k at some Tx/Rx device j, with delayed inner code, fixed inner code

1. Apply IC(M)
2. Apply τ(j)
3. If new outer coding cycle
   - Set new OC(j, k)
   - Current outer code OC(j, k)
4. Apply OC(j, k)

5. Transmit

**Fig. 10**

**PMCW Distance Plot [dB]: SystemPMCW1**

- X: 5.171, Y: 81.48
- X: 10.19, Y: 68.12
- X: 15.14, Y: 65.22

65.2 dB

**Fig. 11**

SUBSTITUTE SHEET (RULE 26)
### A. CLASSIFICATION OF SUBJECT MATTER

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<th>INV.</th>
<th>G01S7/22</th>
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### B. FIELDS SEARCHED

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

G01S

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

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

- EPO-Internal
- INSPEC
- WPI Data

### C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<td>X</td>
<td>HADERER HEINZ ET AL: &quot;Concatenated-code-based phase-coded CW MIMO radar&quot;, 2016 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM (IMS), IEEE, 22 May 2016 (2016-05-22), pages 1-4, XP032941133, DOI: 10.1109/MWSYM.2016.7540109 abstract paragraph [0001] ; figures 1,2</td>
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- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed

- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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- "A" document member of the same patent family

**Date of the actual completion of the international search**

28 June 2018

**Date of mailing of the international search report**

12/07/2018

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<td>X</td>
<td><strong>BOURDOUX A ET AL:</strong> &quot;PMCW waveform and MIMO technique for a 79 GHz CMOS automotive radar&quot; , 2016 IEEE RADAR CONFERENCE (RADARCONF), IEEE, 2 May 2016 (2016-05-02), pages 1-5, XP032908898, DoI: 10.1109/RADAR.2016.7485114 abstract paragraph [Q011]; figures 1,2 paragraphs [00IV], [IV. A]; figure 3</td>
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<td>A</td>
<td><strong>MATousek ZDENEK ET AL:</strong> &quot;Walsh-hadamard sequences for binary encoding of radar signals.&quot; INTERNATIONAL CONFERENCE ON MILITARY TECHNOLOGIES (ICMT) 2015, UNIVERSITY OF DEFENCE, 19 May 2015 (2015-05-19), pages 1-6, XP033172726, DoI: 10.1109/MILTECHS.2015.7153676 abstract paragraphs [0001], [I1.A] - [I1.C]; figures 1-3</td>
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