Performance Analysis of UWB Impulse Radar Using Parallel IPCP Receiver

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***Abstract*— UWB impulse radar has high accuracy of measurement because it uses a transmitted signal whose pulse length is below some nanosecond. In this paper, we propose two novel inter-period correlation processing (IPCP) receivers for UWB impulse radar. The conventional IPCP receiver uses the signal periodicity of signals, so it avoids estimation of unknown parameters determined by the targets and propagation. However, its accuracy of measurement is poor because the time resolution is restricted to a signal periodicity. We propose a parallel IPCP receiver to improve accuracy. When there are multiple targets, the conventional IPCP receiver needs multiple thresholds to detect. This results in complexity of the receiver. So, we propose a parallel differential IPCP receiver. We present the analysis of the outputs, and the performance of proposed receivers.**

I. Introduction

UWB impulse radar has many attractive features for a short range measurement system in Intelligent Transport System (ITS) [1], [2]. An inter period correlation processing (IPCP) system is one of the UWB impulse radars. A transmitted signal of the IPCP system consists of some sequences repeatedly. A receiver uses a signal which delays at pulse repetition period as a reference signal. Because of using the received signal as the reference signal, the receiver avoids the effect of multipath [3]–[5]. This is also suitable for a mobile application like a car because this receiver is simple.

But a time resolution of the IPCP receiver is poor because it is restricted to a signal repetition period. The accuracy of measurement is limited due to the restriction of this.

Further more, the IPCP receiver requires multiple thresholds to detect multiple targets. An output amplitude of the conventional IPCP receiver increases by a number of multipath. So the receiver needs a wide dynamic range. This results in quantization error and complexity of the receiver. It is difficult to set the thresholds to detect because amount of increment of output is not predicted at the receiver.

In this paper, to improve the time resolution, we propose a parallel IPCP receiver. The parallel IPCP receiver is formed in parallel using N IPCPs. The integration time of each IPCP receiver has a time offset. The time resolution of this proposed receiver is less than that of the conventional IPCP receiver. Then the accuracy of measurement is improved.

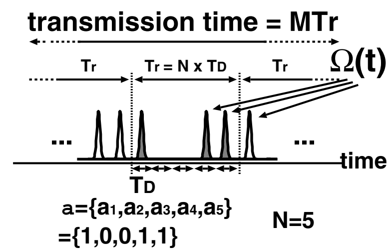

Fig. 1. The transmission signal (N=5).

To avoid multiple thresholds for multiple targets, we also propose a parallel differential IPCP receiver. This receiver is extended from the parallel IPCP receiver and will detect multiple targets using one threshold.

In consideration of a case of multiple targets, we analyze two proposed receivers. We evaluate the detection probability and the accuracy of measurement with the use of computer simulation.

II. System Model

A. Transmitter Model

The transmitted signal is expressed as

$$s_{\text{tr}}(t) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} a_n \Omega(t - nT_D - mNT_D). \qquad (1)$$

Figure 1 illustrates the signal expressed as (1). We denote $\Omega(t)$ as a pulse-shaping waveform and a_n as the nth element in a sequence $\mathbf{a} = \{a_1, a_2, a_3, ..., a_N\}$, where $a_n \in \{0, +1\}$. A signal repetition time is $T_r = NT_D$ where T_D is a pulse duration time. An transmission time is MT_r. We use the generalized Gaussian pulse $\Omega(t) = A\exp\left[-4\pi(\frac{t}{\Delta T})^2\right]$. We denote A as a pulse peak amplitude, ΔT is a parameter which decides the pulse time width, and $\Delta T \leq T_D$ [6]–[8].

We also assume that the transmit antenna is modeled as derivative operation [6], [7]. So the transmitted signal at antenna output is $s'_{\text{tr}}(t)$.

B. Propagation Model

A propagation model is expressed as

$$m(t) = \sum_{i=1}^{L} \alpha_i h(t - \tau_i), \tag{2}$$

where L is a number of targets, and α_i, τ_i[sec] are amplitude ratio and delay time of a reflected signal from ith target respectively[3]. A distance to the ith target is d_i. A relation between d_i and τ_i is $\tau_i = \frac{2d_i}{c}$ where c denotes the velocity of light. We assume $0 < d_1 < d_2 < \dots < d_L$, that is, $0 < \tau_1 < \tau_2 < \dots < \tau_L$. The parameter α_i is decided by the following power attenuation,

$$P_{Ri} = P_t \frac{X_i}{(4\pi d_i^2)^2}, \tag{3}$$

where P_t is a power of the transmitted signal, P_{Ri} is a power of the received signal reflected by ith target, and X_i is a coefficient decided by a antenna gain, its effective area, and radar cross section of the target [9].

In this paper, to evaluate of the characteristics of the proposed receivers, we consider only a direct path from each target. We ignore the effect of the multipath fading between the transmitter and receiver, and clutter from ground. We assume that the received signal from a different target is independent.

C. Receiver Model

The received signal is represented as $r(t) = s_{\text{re}}(t) + n(t)$, where $n(t)$ is AWGN (additive white Gaussian noise) with variance σ^2. The received antenna is also modeled as derivative operation [6], [7]. Considering existence of L targets, the received signals is expressed as

$$s_{\text{re}}(t) = \sum_{i=1}^{L} \alpha_i s''_{\text{tr}}(t - \tau_i) \equiv \sum_{i=1}^{L} s_i(t). \tag{4}$$

The energy of signal from ith target is

$$E_i = \int^{T_r} s_i^2(t) dt. \tag{5}$$

The distance d_i to the target is derived from the relative delay time τ_i.

In this paper, we consider three UWB impulse radar receivers as follow:

- IPCP receiver (conventional)
- parallel IPCP receiver (proposal 1)
- parallel differential IPCP receiver (proposal 2)

III. IPCP RECEIVER

The IPCP receiver uses the received signal as the reference signal. The receiver model is shown in Fig.2. The output is expressed as

$$U(nT_r) = \int_{nT_r}^{(n+1)T_r} r(\xi) r(\xi - T_r) d\xi, \tag{6}$$

where n is a natural number.

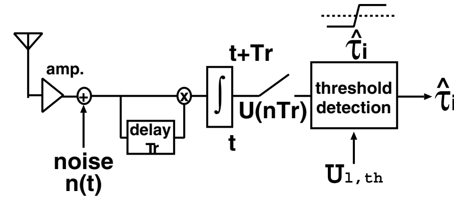

Fig. 2. The block diagram of IPCP receiver.

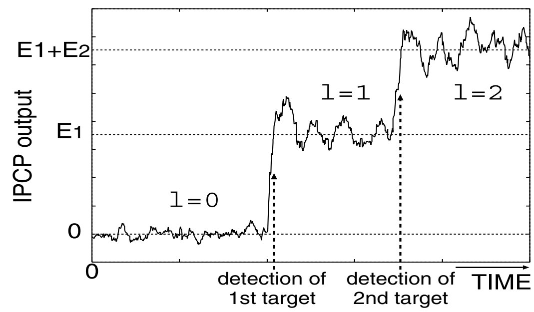

Fig. 3. The output of the IPCP receiver.

A. The output of the receiver, and the estimation of the propagation delay time

We consider the case in which signals reflected from l targets are inputted to the IPCP receiver. The output of the IPCP receiver is expressed as

$$U_l(nT_r) = \int_{nT_r}^{(n+1)T_r} \left\{ \sum_{i=1}^{l} s_i(\xi) + n(\xi) \right\} \cdot \left\{ \sum_{i=1}^{l} s_i(\xi - T_r) + n(\xi - T_r) \right\} d\xi. \tag{7}$$

Figure 3 shows an example of the IPCP receiver output in the case $l = 2$. A mean and variance value are

$$E[U_l(nT_r)] = \sum_{i=1}^{l} E_i \tag{8}$$

$$Var[U_l(nT_r)] = \sigma^4 T_r + 2\sigma^2 \sum_{i=1}^{l} E_i. \tag{9}$$

The mean value changes when the signal reflected from each target is inputted to the IPCP receiver. To detect the signal reflected from lth target, the IPCP receiver needs a threshold $U_{l,\text{th}}$ as follows

$$\sum_{i=1}^{l-1} E_i < U_{l,\text{th}} < \sum_{i=1}^{l} E_i \tag{10}$$

The receiver detects the changes of the mean value with the use of this threshold. The relative delay time $\hat{\tau}_l$ of the reflected signal is estimated as the first nT_r which fulfills the following equation,

$$U(nT_r) > U_{l,\text{th}} \tag{11}$$

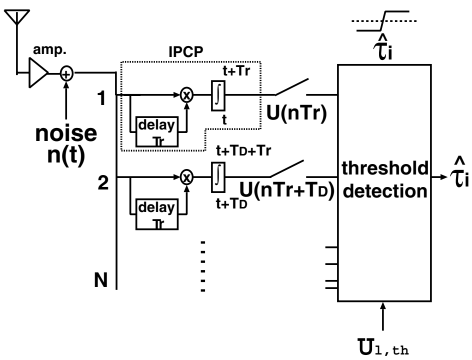

Fig. 4. The block diagram of parallel IPCP receiver.

B. The detection probability and the accuracy of measurement

The threshold $U_{l,\text{th}}$ is decided from the output distribution and a false alarm rate P_F,

$$P_F = \int_{U_{l,\text{th}}}^{\infty} p_{l-1}(U)dU \tag{12}$$

where $p_l(U)$ is a probability distribution function of $U_l(nT_r)$. A detection probability P_D is

$$P_D = \int_{U_{l,\text{th}}}^{\infty} p_l(U)dU \tag{13}$$

where we approximate distribution $p_{l-1}(U)$ and $p_l(U)$ as Gaussian.

We consider the accuracy of measurement. From (11), the time resolution of the IPCP receiver is T_r which is set as a time interval of the integration. The time resolution and the accuracy of measurement have a proportionality relation. From above, the accuracy of measurement about the IPCP receiver is restricted to T_r.

IV. Parallel IPCP Receiver

To improve the time resolution of the IPCP receiver, we propose a parallel IPCP receiver. This receiver model is shown in Fig.4. The parallel IPCP receiver consists of N IPCPs in parallel. The integration time of each IPCP receiver has a time offset T_D. So the time resolution of each IPCP receiver is T_r, but in total, T_D because the receiver outputs at every T_D like $U(nT_r), U(nT_r+T_D), U(nT_r+2T_D), ..., U(nT_r+(N-1)T_D)$.

A. The output of the receiver, and the estimation of the propagation delay time

The parallel IPCP receiver consists of N IPCPs. Each IPCP performs as IPCP receiver. Therefore, the parallel IPCP receiver only changes the resolution from T_r to T_D.

In common with IPCP receiver at previous section, the parallel IPCP receiver estimates the relative delay time $\hat{\tau}_i$ of the reflected signal is derived as the first nT_D which fulfills the following equation,

$$U(nT_D) > U_{l,\text{th}}. \tag{14}$$

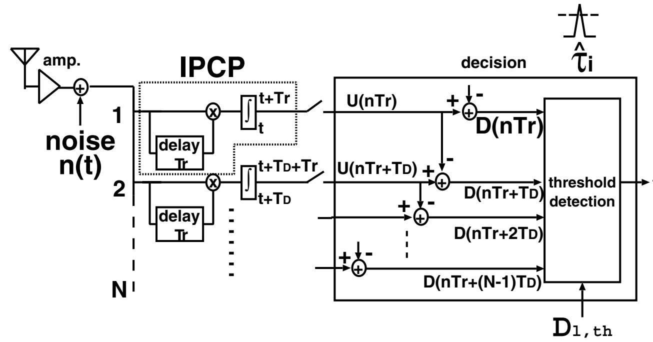

Fig. 5. The block diagram of differential IPCP.

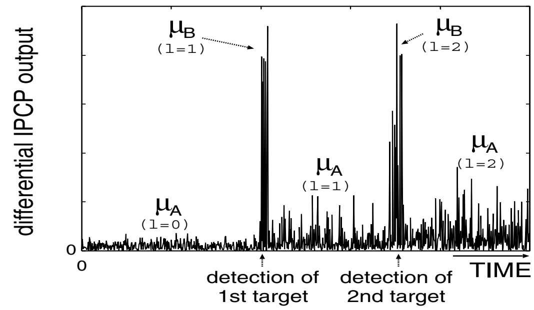

Fig. 6. The parallel differential IPCP receiver output.

B. The detection probability and the accuracy of measurement

We derive $U_{l,\text{th}}$ from (12) like the IPCP receiver. Detection probability is derived by (13) too. Comparing (11) and (14), parallel IPCP receiver improves the time resolution. So, the accuracy of measurement of the parallel IPCP receiver is improved.

V. Parallel Differential IPCP Receiver

From (10), when there are multiple targets, the conventional IPCP receiver and the parallel IPCP receiver need to set multiple thresholds to detect each target. However, the multiple thresholds may result in increase of complexity. To avoid it, we propose a parallel differential IPCP receiver, as shown in Fig.5. This receiver is extended from the parallel IPCP receiver. With the use of $U(nT_r)$, the output of the parallel differential IPCP receiver $D(nT_r)$ is expressed as

$$D(nT_r) = U(nT_r) - U(nT_r - T_D). \tag{15}$$

Figure 6 shows an example of the parallel differential IPCP receiver outputs in the case $l = 2$. From Figure 6, we expect that the parallel differential IPCP receiver needs only one threshold to detect each target.

A. The output of the receiver, and the estimation of the propagation delay time

We consider a detection of the signal reflected from lth target. We assume two states shown in Fig. 6. One state μ_{A_l} is the state between the peak according to the input of $s_l(t)$ which is reflected from lth target, and the peak according to the input of $s_{l+1}(t)$ which is reflected from $l+1$ th target. Another state μ_{B_l} is a state at a peak according to input of $s_l(t)$. The outputs at state μ_{A_l} is

$$D_{\mu_{A_l}}(nT_D) =$$
$$\int_{nT_D}^{nT_D+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} \left\{\sum_{i=1}^{l} s_i(\xi-T_r)+n(\xi-T_r)\right\} d\xi$$
$$-\int_{(n-1)T_D}^{(n-1)T_D+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} \cdot \left\{\sum_{i=1}^{l} s_i(\xi-T_r)+n(\xi-T_r)\right\} d\xi \tag{16}$$

$$= \int_{(n-1)T_D+T_r}^{nT_D+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} \left\{\sum_{i=1}^{l} s_i(\xi-T_r)+n(\xi-T_r)\right\} d\xi$$
$$- \int_{(n-1)T_D}^{nT_D} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} \left\{\sum_{i=1}^{l} s_i(\xi-T_r)+n(\xi-T_r)\right\} d\xi. \tag{17}$$

A mean and variance value of this output are

$$E[D_{\mu_{A_l}}(nT_D)] = 0 \tag{18}$$

$$Var[D_{\mu_{A_l}}(nT_D)] = 2\sigma^4 \frac{T_r}{N} + 2\sigma^2 \sum_{i=1}^{l} \frac{E_i}{N}. \tag{19}$$

The outputs at another state μ_{B_l} is

$$D_{\mu_{B_l}}(nT_D) =$$
$$\int_{nT_D}^{\tau_l+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} n(\xi-T_r)d\xi$$
$$+\int_{\tau_l+T_r}^{nT_D+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} \left\{\sum_{i=1}^{l} s_i(\xi-T_r)+n(\xi-T_r)\right\} d\xi$$
$$-\left[\int_{(n-1)T_D}^{\tau_l+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} n(\xi-T_r)d\xi\right.$$
$$\left.+\int_{\tau_l+T_r}^{(n-1)T_D+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} \left\{\sum_{i=1}^{l} s_i(\xi-T_r)+n(\xi-T_r)\right\} d\xi\right] \tag{20}$$

$$= \int_{(n-1)T_D+T_r}^{nT_D+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} \sum_{i=1}^{l} s_i(\xi-T_r)d\xi$$
$$+\int_{(n-1)T_D t+T_r}^{nT_D+T_r} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} n(\xi-T_r)d\xi$$
$$-\int_{(n-1)T_D}^{nT_D} \left\{\sum_{i=1}^{l} s_i(\xi)+n(\xi)\right\} n(\xi-T_r)d\xi \tag{21}$$

A mean and variance value of this output are

$$E[D_{\mu_{B_l}}(nT_D)] = \frac{E_l}{N} \tag{22}$$

$$Var[D_{\mu_{B_l}}(nT_D)] = 2\sigma^4 \frac{T_r}{N} + 2\sigma^2 \sum_{i=1}^{l-1} \frac{E_i}{N} + 3\sigma^2 \frac{E_l}{N}. \tag{23}$$

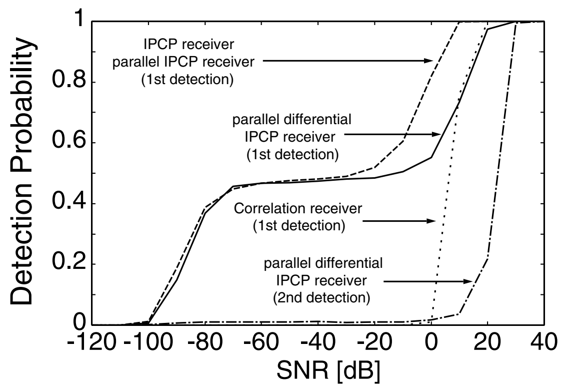

Fig. 7. The detection probability ($P_F = 10^{-4}$).

To detect the targets, the parallel differential IPCP detects the peak value, where the mean value change from 0 to some value at state μ_{B_l}. Thus,

$$0 < D_{l,\mathrm{th}} < \frac{E_l}{N}. \tag{24}$$

The relative delay time $\hat{\tau}_i$ of the reflected signal $s_l(t)$ is estimated as first nT_D which fulfills the following equation,

$$D(nT_D) > D_{l,\mathrm{th}} \tag{25}$$

B. The detection probability and the accuracy of measurement

We derive $D_{l,\mathrm{th}}$ from the output distribution and a false alarm rate P_F,

$$P_F = \int_{D_{l,\mathrm{th}}}^{\infty} p_{\mu_{A_{l-1}}}(D)dD. \tag{26}$$

The detection probability of IPCP receiver is expressed as,

$$P_D = \int_{D_{l,\mathrm{th}}}^{\infty} p_{\mu_{B_l}}(D)dD. \tag{27}$$

We denote $p_{\mu_{A_l}}(D)$ and $p_{\mu_{B_l}}(D)$ are probability distribution functions of $D_{\mu_{A_l}}(nT_D)$, $D_{\mu_{B_l}}(nT_D)$ respectively. We approximate these distributions as Gaussian. From (26), in the case using Neumann-Pearson criterion and keeping P_F constant, the parallel differential IPCP receiver needs multiple thresholds because $p_{\mu_{A_{l-1}}}(D)$ in (26) is changed by the each reflected signal.

VI. Numerical Examples

A. The detection probability

We consider a detect probability of each receiver. It is assumed that there are two targets in the place of 1m and 2m of distance. We consider detection of first target. From (12) and (26), we derive the threshold in the case of $P_F = 10^{-4}$. We calculate P_D using (13) and (27). For comparison, we also derive the correlation receiver. The results are shown in Fig. 7. We define SNR as

$$\overline{SNR}[dB] = 10\log_{10} \frac{E\left[\int^{T_r} s_{\mathrm{re}}^2(t)dt\right]}{\sigma^2}. \tag{28}$$

TABLE I

THE SIMULATION PARAMETERS.

Pulse width:ΔT	6.94×10^{-12}[sec]
Pulse duration:T_D	1.39×10^{-11}[sec]
Number of pulses in T_r:N	16 pulses
code sequence:a_n	1 (for any n)
distance to targets [m]	$d_1 = 1$, $d_2 = 2$

For all SNR range, the performance of these receivers using IPCP is better than that of the correlation receiver. The reason is that when the received signal is absent from the reflected signal, the variance of the receivers output using IPCP is much smaller than that of the correlation receiver.

At middle SNR range, the parallel IPCP receiver and the parallel differential IPCP receiver show the same characteristic. In the parallel IPCP receiver and the parallel differential IPCP receiver, the variance of the case that the received signal is absent from the reflected signal are much smaller than that of the case that the received signal includes the reflected signal.

At high SNR range, the performance of the parallel IPCP receiver is better than that of the parallel differential IPCP receiver. Because the mean value of the parallel differential IPCP receiver is less than that of the parallel IPCP receiver when the received signal includes the reflected signal.

In the case of 2nd target detection, the threshold is decided using Neumann-Pearson criterion and keeping P_F constant. The detection probability of the 2nd target is lower than that of the 1st detection. Because the signal energy reflected from 2nd target is less than that from 1st target, and the threshold for the detection of 2nd target is larger than that of 1st target.

B. The accuracy of measurement

To discuss the accuracy of measurement of each receiver, we evaluate a mean estimate error of measurement using a computer simulation. The mean estimate error (MEE) is defined as

$$\mathrm{MEE} = E[|\hat{d}_l - d_l|], \tag{29}$$

where $\hat{d}_l = \frac{c\hat{\tau}_l}{2}$. We consider the case of two targets, that is $L = 2$. The simulation parameters are shown in Table I. The thresholds to detect targets are decided using Neumann-Pearson criterion and keeping P_F constant. The results are shown in Fig.8.

The mean estimate error of the parallel IPCP receiver and the parallel differential IPCP receiver formed in parallel are improved, because the proposed receivers in parallel have the time resolution T_D ($< T_r$). The mean estimate error of the parallel differential IPCP receiver is lager than that of parallel IPCP receiver. The parallel differential IPCP receiver provides some error because the variance of the parallel differential IPCP receiver is lager than that of parallel IPCP receiver to each mean value.

About the 2nd detection, since the detection probability of the 2nd target is lower than that of the 1st target, although the characteristic of the detection probability for the 2nd target shifts to high SNR, the mean estimate error of the 1st target and that of the 2nd target shows the same characteristic to the increment of SNR.

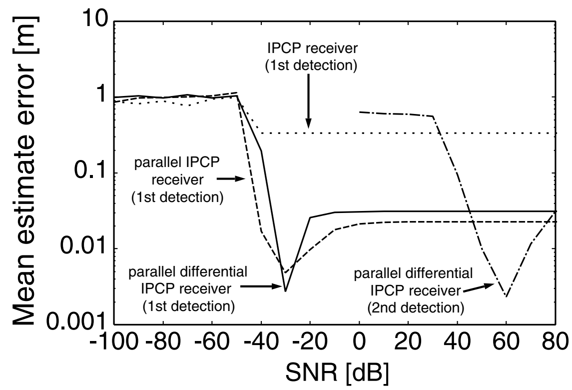

Fig. 8. The mean estimate error ($P_F = 10^{-4}$).

VII. CONCLUSION

In this paper, we have demonstrated the supeority of paralleld IPCP receivers, those improve the accuracy of measurements over the conventional IPCP receivers. For multiple targets, it expected that the parallel differential IPCP receiver could detect using single threshold. However, to keep the false alarm rate constant, the parallel differential IPCP receiver needs multiple thresholds.

AKNOWLEDGMENT

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