# Delay-Sum Antenna Array Reception for Transmitted-Reference Impulse Radio (TR-IR) Systems

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*Abstract*—For transmitted-reference impulse radio (TR-IR), the conventional antenna array reception will provide array gain and thus improve system bit-error-rate (BER) performance. In this paper, we propose a delay-sum antenna array autocorrelation receiver for the TR-IR systems. Simulation results show that by exploiting spatial correlations between antenna array elements, an extra system performance improvement of 1.3 dB and 2.1 dB can be achieved by the proposed receiver at  $BER=10^{-5}$  for the antenna array with 2 and 4 elements, respectively, in the proposed ultra-wideband channel model.

*Index Terms*—Transmitted-reference (TR), impulse radio (IR), autocorrelation receiver (AcR), antenna array, ultra-wideband (UWB).

## I. INTRODUCTION

MPULSE radio, a low-complexity technology for commercial ultra-wideband (UWB) transmission, typically transmits a train of ultra-short data modulated pulses having duration on the order of a nanosecond [1]. This extremely short pulse duration allows the individual multipath components in a scattering rich UWB environment to be resolved and harnessed. Rake reception, although well known for its capability to harness multipath energy, requires very accurate acquisition and channel estimation [2]-[5], and also a large number of Rake fingers to match the number of multipath components. This can be as large as several hundreds in an UWB environment [6]. The design of a practical Rake receiver for impulse radios is thus a challenging task. To avoid the need for stringent acquisition and channel estimation requirements, transmitted-reference impulse radios employing an autocorrelation receiver (TR-IR/AcR) have been proposed [7]-[18] as an alternative. The idea behind TR-IR/AcR is to exploit multipath diversity in slowly time-varying channels by coupling one or more data modulated pulses with one or more unmodulated reference (or pilot) pulses. The received pilot pulses are then used to form the correlator template for symbol detection.

UWB systems are required to transmit signal with extremely low power spectral density [19]. To satisfy the requirement, the signal-to-noise ratio (SNR) performance of UWB systems should be improved as much as possible. This can be done

Manuscript received September 27, 2007; revised January 9, 2008; accepted April 24, 2008. The associate editor coordinating the review of this paper and approving it for publication was M. Z. Win.

This work was supported by the National University of Singapore under Grant R-263-000-436-123.

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Digital Object Identifier 10.1109/T-WC.2008.071067

with the help of antenna array reception. The conventional antenna array reception combines the decision statistics obtained from multiple antenna array elements to provide array gain. Principles of antenna array reception for impulse radio systems have been studied in [20]. In [20], Hussain used generalized Gaussian pulses and showed that an impulsearray beamforming yields sidelobe-free directivity peak-power pattern. It was further shown that the energy pattern and the angular resolution decrease with increasing array size and signal bandwidth. In [21]-[22], antenna array reception was employed for the coherent Rake reception of the impulse radio systems.

So far, to the best of authors' knowledge, research works on TR-IR with diversity reception have not been reported. In this paper, we employ the conventional antenna array reception for the TR-IR systems. Besides that, we propose a delay-sum antenna array AcR. Delay-sum AcR was employed in [16]. In the proposed system [16], each data symbol is transmitted using one pilot pulse-sequence and one data pulse-sequence. At the delay-sum AcR, the received pilot (or data) pulses in one sequence are first delayed to be aligned and summed up to form a composite pilot (or data) pulse. The composite pilot and data pulses are multiplied and integrated to obtain the decision statistic. Simulation results show that by exploiting the correlations of the received pulses in a pulse-sequence, the system SNR performance can be improved. When the elements of antenna array get very close to one another, there exists high correlation between the channel responses of the elements. Inspired by the delay-sum AcR in [16], we may exploit the spatial correlation to improve the system SNR performance.

The rest of the paper is organized as follows. Section II describes the transmitted signal model, the single-input-multipleoutput UWB channel model used for computer simulations, the conventional antenna array AcR and the proposed delaysum antenna array AcR. In Section III, bit-error-rate (BER) performance of the proposed system is derived based on Gaussian approximation. Computer simulation results are provided and discussed in Section IV. We conclude and summarize our paper in Section V.

## **II. SYSTEM MODEL**

## A. Signal Model

In this paper, we consider a peer-to-peer TR-IR system in quasi-static UWB environment. Let  $\cdots b_{-1}b_0b_1b_2\cdots$  denote the sequence of independent and identically distributed data symbols, where  $b_i \in \{-1,1\}$ . Each symbol interval of duration T is divided into  $N_s$  frames, each with a duration of  $T_f$ . In each frame, two pulses are transmitted. The former

is reference pulse and the latter is data-modulated pulse. The transmitted signal is described by

$$s(t) = \sum_{i} \sum_{j=0}^{N_s - 1} \omega(t - iT - jT_f) + b_i \omega(t - iT - jT_f - T_f/2)$$
(1)

where  $\omega(t)$  is a causal pulse of duration  $T_{\omega}$ .

## B. The Channel Model

Various models were proposed for UWB channels, such as [23]-[26]. In this paper, we consider a linear  $(M \times 1)$  antenna array receiver. The channel impulse response that incidents on each array element is generated by using the channel model similar to those described in [22] and [26], where free space path loss model and the lognormal distribution for the multipath gain magnitude were adopted. The channel impulse response consists of multiple clusters and each cluster has multiple rays. Independent fading is assumed for each cluster as well as each ray.

For the  $m^{th}$   $(1 \le m \le M)$  antenna element of the antenna array receiver, we denote the arrival time of the  $p^{th}$  cluster by  $\tau_{p,m}$ , where  $p = 1, 2, \dots, P$ , and the arrival time of the  $q^{th}$  ray measured from the beginning of the  $p^{th}$  cluster by  $\tau_{p,q,m}$ , where  $q = 1, 2, \dots, Q$ . Therefore,  $\tau_{p,1,m} = 0$ . The total number of multipaths is L = PQ. The channel impulse response from a transmitter to the  $m^{th}$  antenna element of the antenna array receiver can be written, in general, as

$$g_m(t) = \sum_{p=1}^{P} \sum_{q=1}^{Q} \alpha_{p,q,m} \delta(t - \tau_{p,m} - \tau_{p,q,m})$$
(2)

where  $\alpha_{p,q,m}$  denotes the amplitude of the  $q^{th}$  ray within the  $p^{th}$  cluster at the  $m^{th}$  antenna element. In order to simplify the notations, we index the multipaths at the  $m^{th}$  element in ascending order such that the path index l takes a value in  $\{1, 2, \dots, PQ\}$ , where l = pQ + q. Hence, we rewrite (2) as follows

$$g_m(t) = \sum_{l=1}^{L} \alpha_{l,m} \delta(t - \tau_{l,m})$$
(3)

where  $\tau_{l, m} = \tau_{p, m} + \tau_{p, q, m}$ .

In this paper, the channel impulse response from a transmitter to the 1<sup>st</sup> antenna element  $g_1(t)$  is considered as a reference. Because the distance of adjacent antenna array elements, denoted as d, is very small, typically about one centimeter, we assume that each ray in each cluster arrives at the antenna array as a plane wave. By denoting the time delay difference between  $\tau_{l,m}$  and  $\tau_{l,1}$  as  $\epsilon_{l,m}$ , we have

$$|\epsilon_{l,m}| = |\tau_{l,m} - \tau_{l,1}| < \frac{d(m-1)}{c}$$
(4)

where c is the speed of light. Therefore, we model the cluster arrival time difference between  $\tau_{p, m}$  and  $\tau_{p, 1}$  as follows

$$\epsilon_{p,m} = \tau_{p,m} - \tau_{p,1} = \frac{d(m-1)\sin(\varphi_p)}{c}$$
(5)

where  $\varphi_p$  is angel of arrival of the  $p^{th}$  cluster.  $\{\varphi_p; p = 1, 2, \dots, P\}$  are independent with one another and uniformly

distributed over the interval  $[0, 2\pi]$ . The ray arrival time difference between  $\tau_{p,q,m}$  and  $\tau_{p,q,1}$  is as follows

$$\epsilon_{p,q,m} = \tau_{p,q,m} - \tau_{p,q,1}$$
$$= \frac{d(m-1)\sin(\varphi_p + \varphi_{p,q})}{c} - \frac{d(m-1)\sin(\varphi_p)}{c} (6)$$

where  $\varphi_{p,q}$  is offset angle for the  $q^{th}$  ray of the  $p^{th}$  cluster with respect to  $\varphi_p$ . In [27], it was found that  $\varphi_{p,q}$  is best fit to a zero-mean Laplacian distributed random variable with a standard deviation of 38°, which is adopted here. Furthermore,  $\{\varphi_{p,q}; p = 1, 2, \dots, P; q = 1, 2, \dots, Q\}$  are independent with one another and  $\varphi_{p,q}$  is independent with  $\varphi_p$ .

The amplitude coefficient  $\alpha_{p, q, m}$  is defined as

$$\alpha_{p,\,q,\,m} = a_{p,\,q}\xi_{p,\,m}\beta_{p,\,q,\,m} \tag{7}$$

where  $a_{p,q}$  is equiprobable  $\pm 1$  to account for signal inversion due to reflections,  $\xi_{p,m}$  reflects the fading associated with the  $p^{th}$  cluster, and  $\beta_{p,q,m}$  corresponds to the fading associated with the  $q^{th}$  ray of the  $p^{th}$  cluster. The  $\xi_{p,m}\beta_{p,q,m}$  is given by

$$\xi_{p,m}\beta_{p,q,m} = 10^{(\mu_{p,q,m}+n_1+n_2)/20} \tag{8}$$

where  $n_1$  and  $n_2$  are independent Gaussian random variables with zero means and variances  $\sigma_1^2$  and  $\sigma_2^2$ , respectively. In (8),  $n_1$  corresponds to the fading on each cluster and  $n_2$ corresponds to the fading on each ray.

The  $\mu_{p,q,m}$  is given by

$$\mu_{p,q,m} = \frac{10 \ln \Omega_0 - 10\tau_{p,m}/\Phi - 10\tau_{p,q,m}/\phi}{\ln 10} - \frac{(\sigma_1^2 + \sigma_2^2) \ln 10}{20}$$
(9)

where  $\Omega_0$  is the mean energy of the first path of the first cluster,  $\Phi$  is the cluster decay factor, and  $\phi$  is the ray decay factor.

Finally, as in [26], the terms  $\{\alpha_{p,q,m}\}\$  are normalized and multiplied with a lognormal shadowing term such that

$$\sum_{p=1}^{P} \sum_{q=1}^{Q} \alpha_{p,\,q,\,m}^2 = 10^{n_x/20} \tag{10}$$

for  $m = 1, 2, \dots, M$ , where  $n_x$  is a Gaussian random variable with zero mean and variance  $\sigma_x^2$ .

### C. Conventional Antenna Array AcR Reception

For conventional antenna array reception, an AcR multiplies the received pilot and data modulated pulses of each array element and their product is integrated. The outputs of all the AcRs for antenna array are combined to form the decision statistics. In Fig. 1 (a), we show the block diagram of the conventional antenna array AcR reception.

The received signal of the  $m^{th}$  antenna element at the receiver is expressed as follows

$$r_m(t) = \sum_i \sum_{j=0}^{N_s - 1} h_m(t - iT - jT_f) + b_i h_m(t - iT - jT_f - T_f/2) + n_m(t)(11)$$

where

$$h_m(t) = \omega(t) \otimes g_m(t) \tag{12}$$



Fig. 1. Block diagrams of (a) the conventional antenna array AcR and (b) the delay-sum antenna array AcR.

in which  $\otimes$  denotes convolution. In (11),  $n_m(t)$  is lowpass filtered (LPF) additive white Gaussian noise (AWGN) with two-sided power spectral density  $N_o/2$ . The autocorrelation function of  $n_m(t)$  is

$$R_n(\tau) = \mathbb{E}[n_m(t)n_m(t+\tau)]$$
  
=  $N_oW\operatorname{sinc}(W\tau)$  (13)

where W ( $W \gg 1/T$ ) is the bandwidth of the lowpass filter.  $n_m(t)$  is independent with  $n_{m'}(t)$  if  $m \neq m'$ . The ratio,  $E_b/N_o$ , of the system is defined as  $\frac{2N_s}{N_o} \int_0^{T_\omega} \omega^2(t) dt$ .

The filtered received signal is then passed through a correlator with integration interval  $T_{int}$ , which is longer than a pulse duration and shorter than the maximum excess delay of UWB channel, to collect the received signal energy. The AcR implements

$$D_i: \begin{cases} >0; \text{ decide } b_i = +1\\ \le 0; \text{ decide } b_i = -1 \end{cases}$$
(14)

where the decision statistics  $D_i$  is the sum of M correlation values corresponding to the M antenna array elements. The decision statistics  $D_i$  is obtained as follows

$$D_{i} = \sum_{m=1}^{M} \sum_{j=0}^{N_{s}-1} \int_{iT+jT_{f}+T_{f}/2+\lambda}^{iT+jT_{f}+T_{f}/2+\lambda+T_{int}} r_{m}(t)r_{m}(t-T_{f}/2)dt$$
(15)

where  $\lambda$  is the perfect synchronization time. In this paper, we assume perfect channel synchronization and  $\lambda$  is known to the receiver.

## D. Delay-Sum Antenna Array AcR Reception

When the antenna elements get close to one another, there is high correlation between the outputs of any two antenna elements. In Fig. 2, we show the correlation coefficient of two channel responses that incident on two antenna array elements with a distance of 1 cm, which are measurement data from [28], with respect to the time delay  $\varsigma$ . From Fig. 2, if the distance of two antenna array elements is sufficiently small, their cross-correlation coefficient gets very close to one. Therefore, by exploiting the correlation, we can obtain more performance gain than the conventional antenna array reception.

Denote the time delay which achieves the highest crosscorrelation of  $h_1(t)$  and  $h_m(t)$  as  $\gamma_m$ ,

$$\gamma_m = \arg\max_{\varsigma} \int_{\lambda}^{\lambda + T_{int}} h_1(t) h_m(t+\varsigma) dt \qquad (16)$$

where  $\varsigma \in (-(m-1)d/c, (m-1)d/c]$ . It is worth to note that  $\gamma_m$  can be obtained by searching in a very narrow interval. When the distance between adjacent antenna array element is 1 cm, d/c = 0.0333 ns. By assuming that  $\{\gamma_m; m = 1, 2, \dots, M\}$  are known to the receiver, the decision statistics  $D_i$  of the delay-sum antenna array AcR reception is

$$D_{i} = \sum_{j=0}^{N_{s}-1} \int_{iT+jT_{f}+T_{f}/2+\lambda}^{iT+jT_{f}+T_{f}/2+\lambda+T_{int}} \left(\sum_{m=1}^{M} r_{m}(t-\eta+\gamma_{m})\right) \cdot \left(\sum_{m=1}^{M} r_{m}(t-\eta+\gamma_{m}-T_{f}/2)\right) dt$$
(17)

where  $\eta = \max{\{\gamma_1, \gamma_2, \dots, \gamma_M\}}$ . In Fig. 1 (b), we show the block diagram of proposed delay-sum antenna array AcR.

### **III. PERFORMANCE ANALYSIS**

In this section, mathematical formulas for predicting the BER performance of TR-IR system with delay-sum antenna

$$Z_{1} = \sum_{j=0}^{N_{s}-1} \int_{iT+jT_{f}+T_{f}/2+\lambda}^{iT+jT_{f}+T_{f}/2+\lambda+T_{int}} \left( \sum_{m=1}^{M} g_{m}(t-\eta+\gamma_{m}) \otimes s(t) \right) \cdot \left( \sum_{m=1}^{M} g_{m}(t-\eta+\gamma_{m}) \otimes s(t-T_{f}/2) \right) dt$$
  
$$= b_{i}N_{s}\mathcal{E},$$
(19)

$$Z_{2} = \sum_{j=0}^{N_{s}-1} \int_{iT+jT_{f}+T_{f}/2+\lambda}^{iT+jT_{f}+T_{f}/2+\lambda+T_{int}} \left( \sum_{m=1}^{M} g_{m}(t-\eta+\gamma_{m}) \otimes s(t) \right) \cdot \left( \sum_{m=1}^{M} n_{m}(t-\eta+\gamma_{m}-T_{f}/2) \right) dt$$

$$= \sum_{m=1}^{N_{s}-1} \int_{iT+jT_{f}+T_{f}/2+\lambda}^{\lambda+T_{int}} h_{j} \left( \sum_{m=1}^{M} h_{j}(t-\eta+\gamma_{m}) \right) \int_{iT} \left( \sum_{m=1}^{M} n_{m}(t-\eta+\gamma_{m}-T_{f}/2) \right) dt$$
(20)

$$=\sum_{j=0}^{N_s-1}\int_{\lambda}^{\lambda+T_{int}} b_i \left(\sum_{m=1}^m h_m(t-\eta+\gamma_m)\right) \cdot \left(\sum_{m=1}^m n_m(t-\eta+\gamma_m+iT+jT_f)\right) dt,$$

$$N_s-1 \int t^{iT+jT_f+T_f/2+\lambda+T_{int}} \int M dt = 0$$
(20)

$$Z_{3} = \sum_{j=0}^{N_{s}-1} \int_{iT+jT_{f}+T_{f}/2+\lambda}^{iT+jT_{f}+T_{f}/2+\lambda+T_{int}} \left( \sum_{m=1}^{M} g_{m}(t-\eta+\gamma_{m}) \otimes s(t-T_{f}/2) \right) \cdot \left( \sum_{m=1}^{M} n_{m}(t-\eta+\gamma_{m}) \right) dt$$
  
$$= \sum_{j=0}^{N_{s}-1} \int_{\lambda}^{\lambda+T_{int}} \left( \sum_{m=1}^{M} h(t-\eta+\gamma_{m}) \right) \cdot \left( \sum_{m=1}^{M} n(t-\eta+\gamma_{m}+iT+jT_{f}+T_{f}/2) \right) dt,$$
(21)

$$Z_{4} = \sum_{j=0}^{N_{s}-1} \int_{iT+jT_{f}+T_{f}/2+\lambda}^{iT+jT_{f}+T_{f}/2+\lambda+T_{int}} \left(\sum_{m=1}^{M} n(t-\eta+\gamma_{m}-T_{f}/2)\right) \cdot \left(\sum_{m=1}^{M} n(t-\eta+\gamma_{m})\right) dt$$
(22)



Fig. 2. Correlation coefficient of two channel responses that incident on two antenna array elements with distance of 1 cm.

array AcR reception are derived.

From Section II, the decision variable  $D_i$  for TR-IR systems in (17) can be expressed as the superposition of four terms

$$D_i := Z_1 + Z_2 + Z_3 + Z_4 \tag{18}$$

where  $Z_1$ ,  $Z_2$ ,  $Z_3$  and  $Z_4$  are shown on the top of the page, in which

$$\mathcal{E} = \int_{\lambda}^{\lambda + T_{int}} \left( \sum_{m=1}^{M} h(t - \eta + \gamma_m) \right)^2 dt.$$
 (23)

In (19 - 22),  $Z_1$  is the desired signal.  $Z_2$ ,  $Z_3$  and  $Z_4$  are noise components. It can be shown that the four terms are all zero mean and uncorrelated with one another.  $Z_2$  and  $Z_3$  are Gaussian, whose conditional variances are [10]

$$\operatorname{Var}[Z_2|\zeta] = \operatorname{Var}[Z_3|\zeta]$$
$$= N_s \int_{\lambda}^{\lambda + T_{int}} \int_{\lambda}^{\lambda + T_{int}} \left( \sum_{m=1}^{M} h(t - \eta + \gamma_m) \right)$$

$$\cdot \left(\sum_{m=1}^{M} h(u - \eta + \gamma_m)\right) R_n(t - u) dt du \quad (24)$$

where  $\zeta$  represents  $\{h_m(t); m = 1, 2, \dots, M\}$ . As a second, and coarser, approximation, we let

$$R_n(\tau) \simeq \frac{N_o}{2} \delta(\tau) \tag{25}$$

on the basis that  $R_n(\tau)$  appears almost impulse like for sufficiently large bandwidth-time product,  $WT_{int}$ . Applying (25) in (24), it is straightforward to show that

$$\operatorname{Var}[Z_2|\zeta] = \operatorname{Var}[Z_3|\zeta] \simeq \frac{N_o}{2} N_s M \mathcal{E}.$$
 (26)

 $Z_4$  is the integral of the product of two uncorrelated Gaussian processes. It can be seen as approximately Gaussian by invoking the central limit theorem, when the bandwidthtime product,  $WT_{int}$ , is large. The condition is true because generally  $W \gg 1/T_{int}$ . The variance of  $Z_4$  is [10]

$$\operatorname{Var}[Z_4] \simeq \frac{N_o^2 N_s M^2 W T_{int}}{2}.$$
 (27)

Therefore, the conditional BER for TR-IR system with delaysum antenna array AcR is

$$P_{DS}(e|\zeta) = \mathcal{Q}\left(\frac{N_s \mathcal{E}}{\sqrt{N_o N_s M \mathcal{E} + \frac{N_o^2 N_s M^2 W T_{int}}{2}}}\right)$$
(28)

where  $Q(z) = (1/\sqrt{2\pi}) \int_{z}^{\infty} \exp(-y^2/2) dy$ . In the similar manner, we can obtain the conditional BER for conventional antenna array AcR reception as follows

$$P_C(e|\zeta) = \mathcal{Q}\left(\frac{N_s \widetilde{\mathcal{E}}}{\sqrt{N_o N_s \widetilde{\mathcal{E}} + \frac{N_o^2 N_s M W T_{int}}{2}}}\right)$$
(29)

where

$$\widetilde{\mathcal{E}} = \sum_{m=1}^{M} \int_{\lambda}^{\lambda + T_{int}} h^2(t) dt.$$
(30)



Fig. 3. BER versus  $E_b/N_o$ ; simulation results of TR-IR system with the conventional antenna array AcR and the proposed delay-sum antenna array AcR using UWB channel model.



Fig. 4. BER versus  $E_b/N_o$ ; simulation results of TR-IR system with the conventional antenna array AcR and the proposed delay-sum antenna array AcR using measurement data.

Comparing (28) and (29), the proposed delay-sum antenna array AcR achieves a directional antenna array gain over the conventional antenna array AcR. The maximum gain is obtained when  $h_1(t) = h_m(t + \gamma_m)$  for  $m = 2, 3, \dots, M$ . Under above condition,  $\operatorname{Var}[Z_4]$  can be omitted when SNR is high and hence the gain for the proposed scheme is about  $10 \times \log_{10}(\sqrt{M})$  dB. It is also noted that the gain is independent of  $N_s$ .

### **IV. SIMULATION RESULTS**

In this section, we present computer simulation results to validate our design. In all cases, the sampling interval is 0.05 ns. The bandwidth of the lowpass filter is 10 GHz. As in [1], we select the shape of the pulse  $\omega(t)$ to be the second derivative of a Gaussian pulse, namely,  $[1 - 4\pi(t/u)^2] \exp[-2\pi(t/u)^2]$ , where u = 0.2877 ns. In the legends of our BER plots, "Simu" represents the BER performance obtained by computer simulation of the overall transmission chain while "Theo" denotes numerical results obtained using (28) and (29).

## A. UWB Channel Model

In Fig. 3, we compare the BER performances of the TR-IR with conventional antenna array AcR (denoted as "C" in the legend) and the delay-sum antenna array AcR (denoted as "DS" in the legend) in the proposed UWB channel model, whose parameters are the same with that of  $4 \sim 10$  meters' range with non-line-of-sight (NLOS) UWB channel model (CM 3), in [26]. For both systems, the number of frames per symbol,  $N_s$ , the frame duration,  $T_f$ , and the integration interval,  $T_{int}$ , are chosen to be 8, 120 ns and 37.55 ns, respectively. The distance between adjacent antenna array elements is 1 cm. The simulation results show that by employing the proposed delay-sum antenna array AcR, an extra gain of about 1.3 dB and 2.1 dB can be achieved at BER=  $10^{-5}$  for M = 2 and 4, respectively.

## B. UWB Channel Measurement Data

Here, the UWB channel impulse response comprises a set of measurement data obtained from [28]. In Fig. 4, we compare the BER performances of TR-IR with conventional antenna array AcR and the delay-sum antenna array AcR. The NLOS situation is considered. The BERs are simulated by averaging the system performance over a permutation of paired-channel measurements made with the adjacent receive antennas array elements spaced at 1 cm apart. The system parameters are  $N_s = 8$ ,  $T_f = 100$  ns, and  $T_{int} = 26.55$  ns. Fig. 4 shows that a performance improvement of about 1.3 dB or 2.1 dB at BER=  $10^{-5}$  can be achieved for M = 2 and 4, respectively, by the proposed delay-sum scheme.

### V. CONCLUSIONS

In this paper, we have proposed a delay-sum antenna array AcR for the TR-IR system. Simulation results have shown that the proposed receiver has better performance than the conventional antenna array AcR when the distance between the adjacent antenna array elements is small. This is because under above situation, there exists high correlation between the channel responses at the antenna array elements. The system performance can be improved by exploiting the spatial correlations.

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