Transmitted-Reference Impulse Radio Systems Based on Selective Combining

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***Abstract*—Transmitted-reference impulse radio with autocorrelation receiver (TR-IR/AcR) generally requires wideband analog delay line (WADL) with length of several tens nanoseconds. To maximally reduce the length, we propose a TR-IR system based on selective combining, which intelligently selects integration regions for symbol detection. It was shown that when the WADL with a total length of 8 ns is employed, the proposed system has a signal-to-noise ratio gain of 0.5 dB, 2.3 dB, 2.3 dB and 3.7 dB over the TR-IR/AcR at bit-error-rate of 10^{-5} for ultra-wideband channel models CM $1 \sim 4$, respectively.**

***Index Terms*—Transmitted-reference (TR), impulse radio (IR), selective combining (SC), ultra-wideband (UWB).**

I. Introduction

TRANSMITTED-reference impulse radios (including differential transmitted-reference impulse radios) with autocorrelation receiver (TR-IR/AcR) have been proposed in [1]-[11]. 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 AcR delays the received pilot pulses to perfectly align with the data modulated pulses and their product is integrated for symbol detection.

The implementation of AcR generally requires wideband analog delay line (WADL) with length of several tens nanoseconds. However, to design WADL with such length in the low-power integrated circuit is daunting [12], [13]. In [13], Bagga et al proposed a quantized WADL, which digitalizes the analog signal, delays the digitalized signal using D-latches, and finally converts the digitalized signal back to analog signal. As shown in Fig. 1, the quantized WADL is comprised of a quantizer, multiple binary delay lines and an adder circuit. The quantizer consists of a series of comparators, each one comparing the input signal to a unique reference voltage at a specific sampling rate. Each comparator output connects to a series of D-latches, which constitute a binary delay line. Thus, the multiple binary delay lines are able to store the digitalized wideband analog signal of a specific time duration. The signal can be retrieved by adding all the outputs of binary delay lines using the adder circuit.

From the description above, we know that the length of WADL is equal to the signal duration stored in the batches of binary delay lines. The number of D-latches in a binary delay line is dictated by the signal bandwidth and duration required to be stored. Since the signal bandwidth is certain, the system complexity and power consumption linearly increase with the signal duration to be stored, i.e. the length of WADL. In [13], simulation results in IBM's CMOS 0.12 μm technology show that the quantized WADL with length of 550 ps requires a total current of 36.7 mA at a 1.6 V power supply. Furthermore, WADL with length in the range of several nanoseconds is feasible at the expense of power.

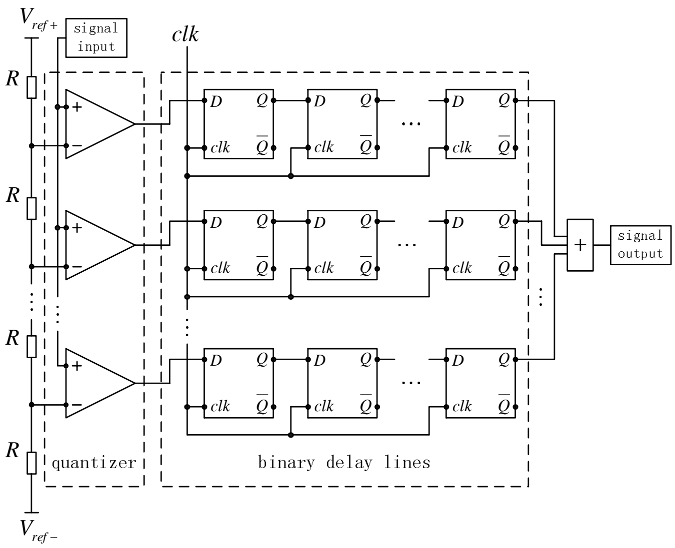

Fig. 1. The structure of quantized WADL.

The WADL is employed to perfectly align the received pilot pulses with the data modulated pulses. Conventionally, the length of WADL is chosen to be the time difference between each data modulated pulse and its corresponding pilot pulse, which is typically longer than the pulse duration plus the maximum excess delay of the channel to preclude intrasymbol interference [5]. From Fig. 1, it is found that wideband analog signal is digitalized and stored by the quantized WADL. The digitalized signal can be delayed to any time instant. We can choose when to store the signal and when to retrieve the signal by modifying the clock signal, denoted as "*clk*" in Fig. 1. At the AcR, only the signal of duration which is equal to the integration interval is required to be stored. The optimal integration interval, which maximizes the signal-to-noise ratio (SNR) at the AcR, can be computed using the method proposed in [14] if a specific ultra-wideband (UWB) channel model is given. It was shown that the optimal integration interval is much shorter than the maximum excess delay of the channel. Therefore, the minimum length of WADL for

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AcR should be equal to the optimal integration interval.

For the non-line-of-sight (NLOS) UWB channels, the optimal integration intervals are still long. To further reduce the required length of WADL, we propose a selective combining receiver for TR-IR system (TR-IR/SC). As TR-IR/AcR, the proposed system transmits pilot pulses as well as data modulated pulses. However, at the receiver, we only store several regions of received pilot signals which have the highest SNR, each region in a WADL. The stored signals are then used to form the correlator template for symbol detection. We will show that to have similar system bit-error-rate (BER) performance as the TR-IR/AcR, TR-IR/SC requires much shorter total length of WADL to store the received signal. Furthermore, the WADL for TR-IR/SC typically has a length of about $1 \sim 3$ ns, which is feasible currently [13]. The proposed system exploits the partial channel information, which is different from both the conventional time-hopping impulse radio with Rake reception (TH-IR/Rake) and TR-IR/AcR. The TH-IR/Rake, although having capability to harness multipath energy, requires very accurate time acquisition and channel estimation [15]. The accurate time acquisition of multipath components is a formidable task. An acquisition error of 0.055 ns will cause the output signal power of demodulator to be reduced by half when the pulse in Fig. 1 of [16] is adopted. The amplitude estimation of multipath components is also not easy. For Rake receivers employing equal ratio combining, which bypass amplitude estimation, the required partial channel information to select Rake fingers is several times more than that of the proposed receiver. Whereas the TR-IR/AcR does not require accurate time acquisition or channel estimation, however, its system performance is poor. The proposed TR-IR/SC does not estimate the exact delay and amplitude of the multipath. It only compares the SNR of different regions in channel response of a pulse and selects the ones with higher SNR. TR-IR/SC provides an ideal tradeoff between the system performance and complexity.

The rest of the letter is organized as follows. Section II describes the conventional TR-IR/AcR. Based on that, we propose the TR-IR/SC system. In Section III, BER performance of TR-IR/SC is derived based on Gaussian approximation [5] and compared with that of TR-IR/AcR. Computer simulation results are provided and discussed in Section IV. We conclude and summarize our letter in Section V.

II. System Description

A. System Model for TR-IR/AcR

In this letter, we consider a peer-to-peer TR-IR system in quasi-static UWB environment. To increase the transmission rate, the former transmitted data modulated pulses are used as pilot pulses for current symbol detection. Therefore, the system model is similar to that in [4], which is called differential TR-IR system.

The sequence of independent and identically distributed data symbols $\cdots b_{-1} b_0 b_1 b_2 \cdots$, where $b_i \in \{-1, 1\}$, is differentially encoded into another symbol sequence $\cdots d_{-1} d_0 d_1 d_2 \cdots$, where $d_i = (b_i d_{i-1}) \in \{-1, 1\}$. For simplicity, each symbol d_i is transmitted using only one data-modulated pulse. Therefore, the transmitted signal is described by

$$s(t) = \sum_i d_i \omega(t - iT) \tag{1}$$

where $\omega(t)$ is a causal pulse with duration T_ω and T denotes the symbol duration.

The transmitted signal propagates through a quasi-static dense multipath fading UWB channel. The random channels are generated according to [17], where the clusters and the rays in each cluster form Poisson arrival processes with different, but fixed rates. The amplitude of each ray is modeled as a lognormal distributed random variable. The channel impulse response model can be written, in general, as

$$g(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l) \tag{2}$$

where L denotes the number of propagation paths, and α_l and τ_l denote, respectively, the amplitude and the delay associated with the l^{th} path. We assume that the signals arriving at the receiver are perfectly time-synchronized and the path delays are normalized with $\tau_1 = 0$. Furthermore, to preclude intersymbol interference and intrasymbol interference, we set $T \geq T_\omega + T_d$, where T_d is the maximum excess delay of the UWB channel. In this letter, maximum excess delay is defined as the period during which the channel power delay profile falls to 20 dB below its maximum value.

The received signal is thus given by

$$r(t) = \sum_i d_i h(t - iT) + n(t) \tag{3}$$

where

$$h(t) = \omega(t) \otimes g(t) = \sum_{l=1}^{L} \alpha_l \omega(t - \tau_l) \tag{4}$$

in which $\otimes$ denotes convolution. In (3), $n(t)$ is lowpass filtered additive white Gaussian noise (AWGN) with two-sided power spectral density $N_o/2$. The autocorrelation function of $n(t)$ is

$$R_n(\tau) = \mathrm{E}[n(t)n(t+\tau)] = N_o W \mathrm{sinc}(W\tau) \tag{5}$$

where W $(W \gg 1/T)$ is the bandwidth of the lowpass filter. The signal-to-noise ratio (SNR), E_b/N_o, of the system is defined as $\frac{1}{N_o}\int_0^{T_\omega} \omega^2(t)dt$.

For the conventional AcR, the received signal is passed through a correlator with integration interval, T_{int}, $(T_\omega \leq T_{int} \leq T_\omega + T_d)$ to collect the received signal energy. The integration interval, T_{int}, determines the amount of multipath and noise energy accumulation. The AcR implements

$$D_i : \begin{cases} > 0; \text{ decide } b_i = +1 \\ \leq 0; \text{ decide } b_i = -1 \end{cases} \tag{6}$$

where the decision variable D_i is

$$D_i = \int_{iT}^{iT+T_{int}} r(t) r(t - T) dt. \tag{7}$$

It is worth to note that because of the implementation of the quantized WADL proposed in [13], the minimum length of WADL required for AcR is T_{int} instead of T.

B. TR-IR Based on Selective Combining

For AcR, the received signal, $r(t)$, $iT < t \leq iT + T_{int}$ is stored as correlator template to detect b_i. Through the study of UWB channel impulse response, it is found that during the interval from 0 to T_d, the signal power fluctuates wildly. It will be desirable to only utilize some regions of $r(t)$, $iT < t \leq iT + T_\omega + T_d$ which have higher SNR than other regions as correlator template. Therefore, for the proposed TR-IR/SC, we partition the UWB channel impulse response $h(t)$ into $M = \lceil (T_\omega + T_d)/T_s \rceil$ regions, where T_s is the duration of each region and $\lceil \bullet \rceil$ denotes integer ceil. The channel response energy arrived in the m^{th} region is

$$\mathcal{E}_m = \int_{(m-1)T_s}^{mT_s} h^2(t)dt. \tag{8}$$

In this letter, we assume that the partial channel information $\mathcal{E}_m$ is available at the receiver. The assumption is realistic. The estimate of $\mathcal{E}_m$, which is denoted by $\widehat{\mathcal{E}}_m$, can be obtained through data-aided estimation. If the first N_p symbols, which are known to the receiver, are transmitted to estimate $\mathcal{E}_m$, we have

$$\widehat{\mathcal{E}}_m = \frac{1}{N_p} \sum_{i=0}^{N_p-1} b_i \int_{iT+(m-1)T_s}^{iT+mT_s} r(t)r(t-T)dt. \tag{9}$$

Arranging $\{\mathcal{E}_m\}_{m=1}^M$ in a decreasing order as

$$\mathcal{E}_{1:M} \geq \mathcal{E}_{2:M} \geq \cdots \geq \mathcal{E}_{M:M} \geq 0, \tag{10}$$

the receiver then selects and combines those regions with $\{\mathcal{E}_{m:M}\}_{m=1}^{N_c}$ for demodulation, which results in the decision variable D_i to be

$$D_i = \sum_{m=1}^{N_c} \int_{iT+(m:M)T_s-T_s}^{iT+(m:M)T_s} r(t)r(t-T)dt. \tag{11}$$

The selective combining receiver block diagram is shown in Fig. 2. From the figure, the conventional AcR can be viewed as a special case of the selective combining receiver with $N_c = 1$ and $T_s = T_{int}$. Comparing with the AcR, the proposed system splits the integration interval into small regions. For each region, the signal duration to be stored, i.e. the length of WADL, is T_s, because the quantized WADL [13] is utilized. Thus, instead of using a WADL with a very long length as in a TR-IR/AcR system, we use multiple WADLs with typical length of several nanoseconds. In doing so, to have the similar system BER performance, TR-IR/SC requires much shorter total length of WADL than TR-IR/AcR, especially for NLOS UWB channels. Although the proposed TR-IR/SC conducts an extra task, that is partial channel information estimation, the estimation complexity is fairly low as described above. This is because in the proposed system, precise time acquisition, which is most difficult for the TH-IR system with Rake reception, is not required.

The duration of one integration region, T_s, is an important system parameter for TR-IR/SC systems. Generally, T_s should be comparable to the pulse duration, T_ω. In practical situation, the choice of T_s depends on the requirement of system performance, complexity and working conditions. If T_s is small (large), the required length of WADL is short (long). However, to obtain partial channel information $\{\mathcal{E}_m; m = 1, 2, \cdots, M\}$ is time-consuming (time-saving) because M is large (small).

III. Performance Analysis

In this section, mathematical formulas for predicting the TR-IR/SC system BER performance are derived and compared with those for the TR-IR/AcR system.

From Section II, the decision variable D_i for TR-IR/SC systems in (11) can be expressed as the superposition of four terms

$$D_i := Z_1 + Z_2 + Z_3 + Z_4 \tag{12}$$

where

$$\begin{aligned} Z_1 &:= \sum_{m=1}^{N_c} \int_{iT+(m:M)T_s-T_s}^{iT+(m:M)T_s} d_i d_{i-1} h^2(t-iT)dt \\ &= b_i \sum_{m=1}^{N_c} \mathcal{E}_{m:M}, \end{aligned} \tag{13}$$

$$\begin{aligned} Z_2 &:= \sum_{m=1}^{N_c} \int_{iT+(m:M)T_s-T_s}^{iT+(m:M)T_s} d_i h(t-iT) \cdot n(t-T)dt \\ &= d_i \sum_{m=1}^{N_c} \int_{(m:M)T_s-T_s}^{(m:M)T_s} h(t) \cdot n(t+iT-T)dt, \end{aligned} \tag{14}$$

$$\begin{aligned} Z_3 &:= \sum_{m=1}^{N_c} \int_{iT+(m:M)T_s-T_s}^{iT+(m:M)T_s} d_{i-1} h(t-iT) \cdot n(t)dt \\ &= d_{i-1} \sum_{m=1}^{N_c} \int_{(m:M)T_s-T_s}^{(m:M)T_s} h(t) \cdot n(t+iT)dt, \end{aligned} \tag{15}$$

$$Z_4 := \sum_{m=1}^{N_c} \int_{iT+(m:M)T_s-T_s}^{iT+(m:M)T_s} n(t-T) \cdot n(t)dt. \tag{16}$$

In (12 - 16), 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 the same and given by [5]

$$\begin{aligned} \mathrm{Var}[Z_2|h(t)] = \mathrm{Var}[Z_3|h(t)] = \sum_{m=1}^{N_c} \int_{(m:M)T_s-T_s}^{(m:M)T_s} \\ \int_{(m:M)T_s-T_s}^{(m:M)T_s} h(t)h(\tau)R_n(t-\tau)dtd\tau. \end{aligned} \tag{17}$$

As a second, and coarser, approximation, we let

$$R_n(\tau) \simeq \frac{N_o}{2}\delta(\tau) \tag{18}$$

on the basis that $R_n(\tau)$ appears almost impulse like for sufficiently large bandwidth-time product, $N_c W T_s$. Applying (18) in (17), it is straightforward to show that

$$\mathrm{Var}[Z_2|h(t)] = \mathrm{Var}[Z_3|h(t)] \simeq \frac{N_o}{2} \sum_{m=1}^{N_c} \mathcal{E}_{m:M}. \tag{19}$$

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 bandwidth-time product, $N_c W T_s$, is large. The condition is true because

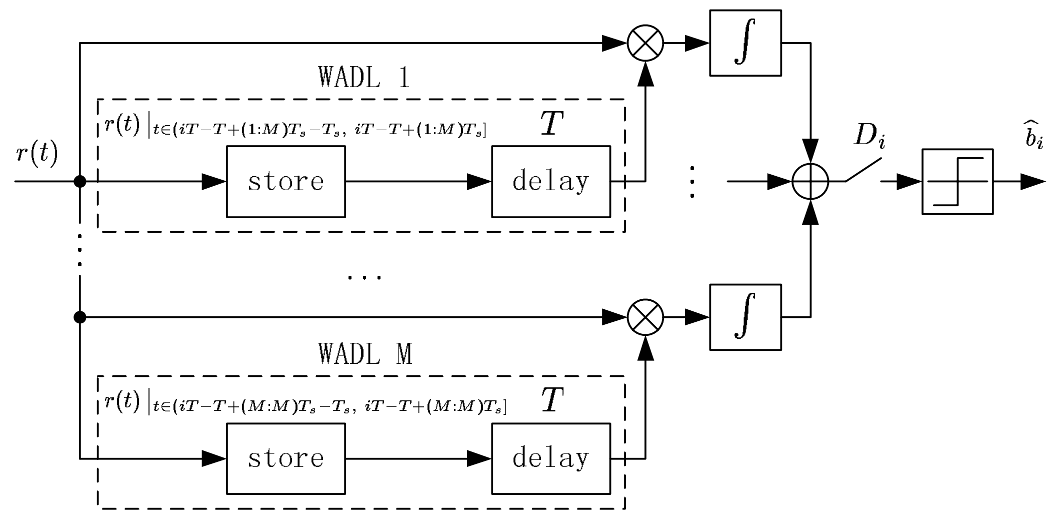

Fig. 2. The selective combining receiver block diagram for TR-IR.

generally $W \gg 1/(N_cT_s)$. The variance of Z_4 is [5]

$$\mathrm{Var}[Z_4] \simeq \frac{N_cN_o^2WT_s}{2}. \tag{20}$$

Therefore, the conditional BER for TR-IR/SC is

$$P_{\mathrm{SC}}(e|h(t)) = Q\left(\frac{\sum_{m=1}^{N_c}\mathcal{E}_{m:M}}{\sqrt{N_o\sum_{m=1}^{N_c}\mathcal{E}_{m:M}+\frac{N_cN_o^2WT_s}{2}}}\right) \tag{21}$$

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

$$P_{\mathrm{AcR}}(e|h(t)) = Q\left(\frac{\mathcal{E}_{T_{int}}}{\sqrt{N_o\mathcal{E}_{T_{int}}+\frac{N_o^2WT_{int}}{2}}}\right) \tag{22}$$

where $\mathcal{E}_{T_{int}} = \int_0^{T_{int}} h^2(t)dt$. Comparing (21) and (22), when $T_{int} = N_cT_s$, the performance difference between TR-IR/SC and TR-IR/AcR lies in the difference between $\sum_{m=1}^{N_c}\mathcal{E}_{m:M}$ and $\mathcal{E}_{T_{int}}$. When SNR is high, we may omit the variance of cross-noise term, $\mathrm{Var}[Z_4]$, in both (21) and (22) and express the conditional BER as follows

$$P(e|h(t)) = Q\left(\sqrt{\frac{\mathcal{E}}{N_o}}\right) \tag{23}$$

where $\mathcal{E} = \sum_{m=1}^{N_c}\mathcal{E}_{m:M}$ if a TR-IR/SC system is concerned and $\mathcal{E} = \mathcal{E}_{T_{int}}$ if a TR-IR/AcR system is concerned. Because generally $\sum_{m=1}^{N_c}\mathcal{E}_{m:M} > \mathcal{E}_{T_{int}}$ if $T_{int} = N_cT_s$, the performance improvement of the proposed system is predictable.

IV. Simulation Results

In this section, we present the computer simulation results to validate our design. In all cases, the random channels are generated according to [17]. The sampling interval is 0.125 ns. The bandwidth of the lowpass filter is 4 GHz. As in [16], we select the shape of the pulse $\omega(t)$ to be the second derivative of a Gaussian pulse, namely, $\left[1-4\pi(t/\tau_m)^2\right]\exp[-2\pi(t/\tau_m)^2]$, where $\tau_m = 0.2877$ ns. Furthermore, we assume that the perfect partial channel information $\{\mathcal{E}_m, m = 1,2,\cdots,M\}$ is available at the receiver.

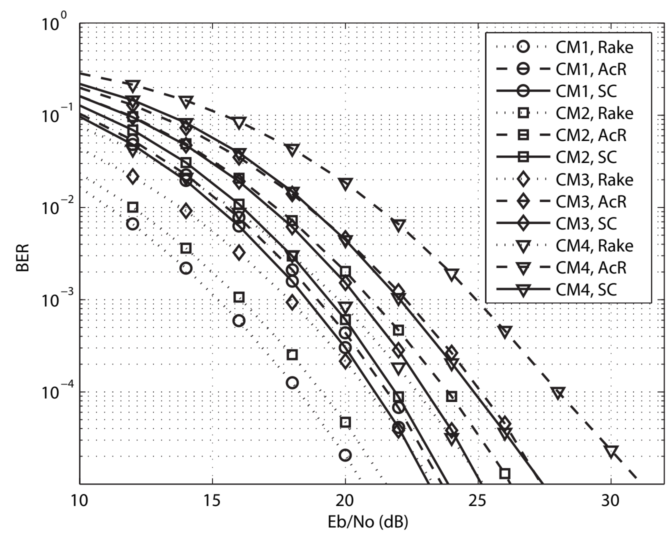

Fig. 3. BER versus E_b/N_o; the selective combining receiver versus AcR and Rake receiver in UWB channel models CM $1 \sim 4$.

In Fig. 3, we compare the BER performance of the TR-IR/SC (denoted as "SC" in the legend) with that of the TR-IR/AcR (denoted as "AcR" in the legend) in UWB channel models CM1, CM2, CM3 and CM4 [17]. For both systems, the same symbol durations T of 40 ns, 50 ns, 70 ns and 120 ns is chosen for CM $1 \sim 4$, respectively. For TR-IR/AcR, T_{int} is set to be 8 ns. For TR-IR/SC, T_s and N_c are chosen to be 2 ns and 4, respectively. Therefore, we have $T_{int} = N_cT_s$. This scenario is reasonable since currently, WADLs with length of several hundreds picoseconds can be manufactured in low-power integrated circuit and a delay time in the range of several nanoseconds is feasible at the expense of power [13]. The simulation results show that by employing selective combining, a SNR gain of about 0.5 dB, 2.3 dB, 2.3 dB and 3.7 dB can be achieved at BER$= 10^{-5}$ for CM $1 \sim 4$, respectively. It is also observed that the proposed TR-IR/SC system has more performance gain in the UWB channel

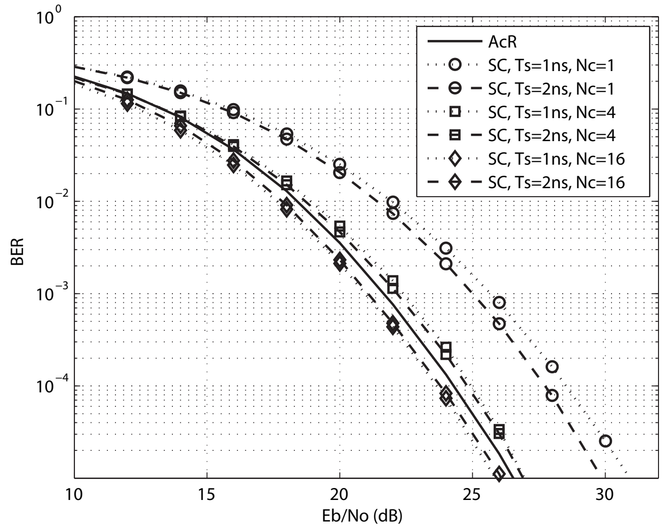

Fig. 4. BER versus E_b/N_o; TR-IR/SC for various values of N_c and T_s in UWB channel model CM4.

without line-of-sight (LOS), such as CM2, CM3 and CM4. This is because in the channel with LOS, the signal energy is concentrated in several first arriving multipath. The AcR with short integration interval, T_{int}, can collect most of the signal power. However, in the non-line-of-sight (NLOS) channels, the signal energy is dispersed into hundreds of multipath located apart. Only AcRs with very long integration interval is able to perform well.

In Fig. 3, we also present the BER performance of the coherent detection of Rake receiver (denoted as "Rake" in the legend). The transmitted signal model is almost the same as that in (1) except that $\{b_i\}$ instead of $\{d_i\}$ is used to modulate the pulses. Assuming perfect channel information is known to the receiver, a 4-finger Rake receiver employs maximum ratio combining to coherently detect the received signals. It is found that the Rake reception outperforms the proposed selective combining receiver about 2.5 dB, 2.3 dB, 1.8 dB and 2.2 dB at BER$= 10^{-5}$ for CM $1 \sim 4$, respectively.

Fig. 4 compares the BER performances of the TR-IR/SC for various values of N_c and T_s in UWB channel model CM4. In Fig. 4, we also present the BER performance of TR-IR/AcR which employs the optimal integration interval, $T_{int} = 50.0$ ns, computed using the method in [14] at the SNR of 20 dB. It is observed that even the TR-IR/SC with $N_c = 4$ and $T_s = 2$ ns is able to achieve similar performance as TR-IR/AcR. Under this condition, the total length of WADL required by the TR-IR/SC is only 1/6.25 of that required by the TR-IR/AcR. It is also found when $N_c = 16$ and $T_s = 1$ ns, the TR-IR/SC has about 0.7 dB SNR gain over the TR-IR/AcR at BER$= 10^{-5}$.

V. Conclusions

In this letter, we have introduced a TR-IR system based on selective combing. Through computer simulations and theoretical analysis, we have demonstrated that when the total length of WADLs is the same, the proposed system is capable of collecting more signal energy and thus has better BER performance than the conventional TR-IR/AcR. On the contrary, when both TR-IR/SC and TR-IR/AcR have similar BER performances, the required length of WADL by the former is much less than that by the latter. Therefore, the proposed system is suitable for the applications where only very short WADL is available.

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