Narrowband Interference Suppression of an MTR-UWB Transceiver

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***Abstract*— A recently proposed multiuser transmitted reference ultra wideband (MTR-UWB) transceiver not only provides much higher data rates than a conventional TR-UWB system, but also enables multiuser communication effectively. This paper further investigates its narrowband interference suppression capability. Effects of different jamming parameters such as the number of jamming tones, jamming power, and data rate ratio of narrowband to UWB signals, are studied. Some insights into trade-offs between suppression of narrowband interfering signals and detection performance are illustrated.** [1]

I. Introduction

Transmitted reference (TR) technology has gained popularity in ultra wideband (UWB) applications [1], [2]. A pair of short pulses is transmitted together, and a UWB receiver can easily demodulate the data pulse by using the reference pulse, irrespective of unknown severe multipath distortion, because both pulses carry the same channel information after propagation. However, this low complexity detection is achieved by sacrificing data rate (half the time the channel is not used for data service), as well as performance degradation (due to the noisy template and lack of effective multiple access methods).

Significant efforts have been made to improve template estimation for better detection performance [2], [3] and to increase the data rate [4]. Recently, a multiuser transmitted reference (MTR) transceiver was proposed to support multiuser communication, where a pair of pseudorandom (PN) spreading sequences are assigned to the reference pulses and data pulses of each user, respectively [5], [6], while inheriting the detection merits from its single user counterpart. Further work on increasing data rate built upon bi-orthogonal signaling has been reported [7], doubling the previous data rate of [5], or equivalently boosting data rate up to four times that of the conventional TR scheme [1].

UWB systems are intended for overlay applications, yet narrowband interference (NBI) may present serious hurdles to UWB services [8]. In this paper, we address the issue of NBI effects in the MTR transceiver. We focus on NBI, both analytically and by simulation, noting that the UWB multiaccess interference in the MTR scheme has been thoroughly studied in [6]. Thus, our signal model consists of one UWB user, plus multiple NBI of different characteristics. However, we still incorporate the features of the MTR system, including PN sequences, in order to conform to the multiuser model.

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II. MTR-UWB Transceiver with Narrowband Interference

Consider a TR UWB system employing frame-rate spreading codes proposed in [6]. We assume a single user system, and focus on NBI suppression. Denote the transmitted pulse of duration T_w by $w(t)$. Each symbol repeats N_f frames, with frame length T_f, and symbol period $T_s = N_f T_f$. If the binary information sequence of the user is $I_n \in \{\pm 1\}$, then the transmitted signal with transmission power P is given by

$$\begin{aligned} s(t) &= \sqrt{\frac{P}{2}} \sum_n [A_n w(t - nT_f) \\ &+ I_{\lfloor n/N_f \rfloor} B_n w(t - nT_f - d_n)], \end{aligned}$$

where A_n and B_n are frame-rate binary PN sequences taking values ± 1, and $d_n = c_n T_c$ is the delay of data pulse controlled by time hopping code c_n. After propagation through the UWB channel, the received signal in the presence of noise and NBI becomes

$$\begin{aligned} r(t) &= \sum_n [A_n h(t - nT_f) + I_{\lfloor n/N_f \rfloor} B_n h(t - nT_f - d_n)] \\ &+ v(t) + \mathcal{I}(t), \end{aligned}$$

where $h(t)$ is the signature waveform depending on the transmitted waveform, power, channel, and the front-end filter [6]. Propagation delay is ignored for simplicity. $v(t)$ represents AWGN noise filtered by an ideal filter confined to $f \in [-\frac{\mathcal{B}}{2}, \frac{\mathcal{B}}{2}]$. $\mathcal{I}(t)$ represents the NBI, assumed to take the following form [8]

$$\mathcal{I}(t) = \sum_{i,l} \sqrt{2\mathcal{P}_i} \cos(2\pi f_i t + \theta_i) b_{i,l} g_i(t - lT_i - \epsilon_i),$$

where $\mathcal{P}_i$, $b_{i,l}$, T_i, θ_i, and $\epsilon_i \in (0, T_i)$ are the transmission power, lth symbol, symbol duration, random phase and delay jitter of the ith NBI signal, respectively.

If we divide the received signal into segments of frame length, and define the m'th segment as $r_{m'}(t) \triangleq r(t + m'T_f)$ for $t \in [0, T_f)$, then in the absence of inter-symbol interference (ISI) we obtain

$$\begin{aligned} r_{m'}(t) &= A_{m'}h(t) + I_{\lfloor m'/N_f \rfloor} B_{m'} h(t - d_{m'}) \\ &+ v_{m'}(t) + \mathcal{I}_{m'}(t). \end{aligned}$$

If N_p frames spanning N_s UWB symbol duration are used for signature waveform (template) estimation, then the estimator has the following form

$$\begin{aligned} \widehat{h}(t) &= \frac{1}{N_p} \sum_{m'=1}^{N_p} A_{m'} r_{m'}(t) \\ &= h(t) + \frac{1}{N_p} \sum_{m'} [I_{\lfloor m'/N_f \rfloor} A_{m'} B_{m'} h(t - d_{m'}) \\ &+ A_{m'} v_{m'}(t) + A_{m'} \mathcal{I}_{m'}(t)]. \end{aligned} \quad (1)$$

Both NBI and noise introduce distortions to the waveform, and will affect detection performance. Consider estimation of the nth UWB symbol, using the received signals $r_m(t)$ for $m = nN_f, \ldots, (n+1)N_f - 1$. The estimated reference signal is first subtracted from the received signal, yielding

$$\begin{aligned} \widetilde{r}_m(t) &= A_m h(t) + I_n B_m h(t - d_m) \\ &+ v_m(t) + \mathcal{I}_m(t) - A_m \widehat{h}(t). \end{aligned}$$

Then data symbol I_n can be estimated based on the average of the N_f correlators' output as

$$\widehat{I}_n = \text{sign}(y^{(n)}), \ y^{(n)} = \frac{1}{N_f} \sum_m \int_0^{T_f} \widehat{h}_k(t) \bar{r}_m(t) dt, \quad (2)$$

where $\bar{r}_m(t) = B_m \widetilde{r}_m(t + d_m)$. It is useful to further express $y^{(n)}$ via its signal and interference components as $y^{(n)} = y_s + y_n$, where

$$y_s = I_n \frac{1}{N_f} \sum_m \int_0^{T_f} \widehat{h}(t) h(t) dt, \quad (3)$$

$$\begin{aligned} y_n = \frac{1}{N_f} \sum_m \int_0^{T_f} & B_m \widehat{h}(t) [A_m h(t + d_m) \\ & - A_m \widehat{h}(t + d_m) + v_m(t + d_m) + \mathcal{I}_m(t + d_m)] dt. \end{aligned} \quad (4)$$

Next, we analyze performance of this symbol detector and waveform estimator in the presence of NBI and noise.

III. Performance Analysis

A. Waveform Estimation Mean-Square-Error

From (1), signature estimation error is readily obtained as

$$\begin{aligned} \delta h(t) &= \widehat{h}(t) - h(t) \\ &= \frac{1}{N_p} \sum_{m'} [I_{\lfloor m'/N_f \rfloor} A_{m'} B_{m'} h(t - d_{m'}) \\ &+ A_{m'} v_{m'}(t) + A_{m'} \mathcal{I}_{m'}(t)]. \end{aligned} \quad (5)$$

To quantify the estimator performance, the estimation mean-square-error (MSE) is defined as

$$\text{MSE} = \int_0^{T_f} E\{\delta h^2(t)\} dt. \quad (6)$$

If the signature spreads over T_f, then the integration interval needs to be correspondingly increased. To evaluate (6), it is sufficient to consider a general term $E\{\delta h(t) \delta h(\tau)\}$. According to (5), and invoking the i.i.d. assumption on PN codes, we have

$$\begin{aligned} E\{\delta h(t) \delta h(\tau)\} &= \frac{1}{N_p^2} \sum_{m'} [h(t - d_{m'}) h(\tau - d_{m'}) \\ &+ E\{v_{m'}(t) v_{m'}(\tau)\} + E\{\mathcal{I}_{m'}(t) \mathcal{I}_{m'}(\tau)\}]. \end{aligned} \quad (7)$$

The noise statistic has been derived in [6] as

$$E\{v_{m'}(t) v_{m'}(\tau)\} = \sigma_v^2 \phi(t - \tau), \quad (8)$$

where $\sigma_v^2 \triangleq \frac{N_0}{2} \mathcal{B}$, and $\phi(t) \triangleq \text{sinc}(\pi \mathcal{B} t)$. Applying the i.i.d. property for NBI symbols, cross terms between different NBI signals disappear. For convenience of analysis, it is reasonable to assume that $T_i >> T_f$. Then, within a UWB frame duration, NBI symbol transitions can be ignored and $g_i(m'T_f + t - lT_i - \epsilon_i)$ can be approximated as a constant, $g_i(m'T_f - l_{m'}^{(i)} T_i - \epsilon_i)$ [8] where $l_{m'}^{(i)}$ is the symbol index of the ith NBI signal in the m'th UWB frame. Consequently,

$$\begin{aligned} E\{\mathcal{I}_{m'}(t) \mathcal{I}_{m'}(\tau)\} &= \sum_i \mathcal{P}_i E\{g_i^2(m'T_f - l_{m'}^{(i)} T_i - \epsilon_i) \\ &\times [\cos(2\pi f_i (t - \tau)) + 2\theta_i \\ &+ \cos(4\pi f_i m' T_f + 2\pi f_i (t + \tau))]\}. \end{aligned} \quad (9)$$

Assume θ_i is independent of ϵ_i, and uniformly distributed in $[0, 2\pi]$. Substituting (8) and (9) into (7), defining average received NBI power over N_p frames as $\sigma_{i,N_p}^2 \triangleq \frac{1}{N_p} \sum_{m'} E\{\mathcal{P}_i g_i^2(m'T_f - l_{m'}^{(i)} T_i - \epsilon_i)\}$, we obtain

$$\begin{aligned} E\{\delta h(t) \delta h(\tau)\} &= \frac{1}{N_p^2} \sum_{m'} h(t - d_{m'}) h(\tau - d_{m'}) \\ &+ \frac{\sigma_v^2 \phi(t - \tau)}{N_p} + \sum_i \frac{\sigma_{i,N_p}^2}{N_p} \cos(2\pi f_i (t - \tau)). \end{aligned} \quad (10)$$

Applying these results, channel MSE is obtained as

$$\text{MSE} = \frac{1}{N_p^2} \sum_{m'} \mathcal{E}_{c_{m'}, c_{m'}} + \frac{\sigma_v^2 T_f}{N_p} + \sum_i \frac{\sigma_{i,N_p}^2 T_f}{N_p}, \quad (11)$$

where $\mathcal{E}_{d_1, d_2} \triangleq \int_0^{T_f} h(t - d_1 T_c) h(t - d_2 T_c) dt$. For simplicity, we also define the following quantities to be used in the subsequent analysis

$$\mathcal{H}_d \triangleq \int \int_0^{T_f} \phi(t - \tau) h(t - dT_c) h(\tau - dT_c) dt d\tau,$$

$$\mathcal{G}_{i,d} \triangleq \int \int_0^{T_f} \cos(2\pi f_i (t - \tau)) h(t - dT_c) h(\tau - dT_c) dt d\tau,$$

$$\mathcal{Y} \triangleq \int\int_0^{T_f} \phi^2(t-\tau)dtd\tau,$$

$$\mathcal{X}_i \triangleq \int\int_0^{T_f} \phi(t-\tau)\cos(2\pi f_i(t-\tau))dtd\tau,$$

$$\mathcal{Z}_{i,j} \triangleq \int\int_0^{T_f} \cos(2\pi f_i(t-\tau))\cos(2\pi f_j(t-\tau))dtd\tau.$$

We also define the ith NBI's received power averaged over the nth UWB symbol duration as

$$\sigma^2_{i,N_f,n} = \frac{1}{N_f}\sum_{m=nN_f}^{(n+1)N_f-1} \mathcal{P}_i E\{g_i^2(mT_f - l_m^{(i)}T_i - \epsilon_i)\}.$$

This term is in contrast to σ^2_{i,N_p}, which is the average received power over N_p frames that are used in signature waveform estimation. If we assume $E\{g_i^2(mT_f - l_m^{(i)}T_i - \epsilon_i)\}$ is constant over all m, then $\sigma^2_{i,N_f,n} = \sigma^2_{i,N_p} = \sigma_i^2 = \mathcal{E}_{NBI,i}/T_i$ where $\mathcal{E}_{NBI,i}$ denotes received NBI symbol energy. Applying the result back to (11), and assuming periodic time hopping codes, MSE can be further simplified as

$$\text{MSE} = \frac{\mathcal{E}_{c,c}}{N_p}\left(1 + \frac{\sigma_v^2 T_f}{\mathcal{E}_{c,c}} + \sum_i \frac{\mathcal{E}_{NBI,i}T_f}{\mathcal{E}_{c,c}T_i}\right). \quad (12)$$

The NBI effect on waveform estimation is determined by the NBI symbol to frame duration ratio T_i/T_f, signal to NBI ratio (SIR) $\mathcal{E}_{c,c}/\mathcal{E}_{NBI}$, and N_p. The more samples collected (larger N_p), the smaller the MSE. Also it is desirable to have smaller frame time T_f for UWB signal transmission (high rate). However, the UWB multiple access interference may become adversely dominant in this case.

B. Detection Performance

If noise plus interference is regarded as Gaussian, then detector bit error rate (BER) can be approximated as $Q(\sqrt{\text{SINR}})$, where SINR is the signal to interference plus noise ratio (SINR), defined as $E\{y_s^2\}/E\{y_n^2\}$. From (3), signal power is

$$E\{y_s^2\} = \mathcal{E}_{0,0}^2 + \int\int_0^{T_f} E\{\delta h(t)\delta h(\tau)\}h(t)h(\tau)dtd\tau.$$

Applying (10), it becomes

$$E\{y_s^2\} = \mathcal{E}_{0,0}^2 + \frac{1}{N_p^2}\sum_{m'}\mathcal{E}^2_{c_{m'},c_{m'}} + \frac{\sigma_v^2\mathcal{H}_0}{N_p} + \sum_i \frac{\sigma^2_{i,N_p}\mathcal{G}_{i,0}}{N_p}.$$

If we define

$$u_m \triangleq B_m[A_m\delta h(t+d_m) + v_m(t+d_m) + \mathcal{I}_m(t+d_m)],$$

then (4) becomes

$$y_n = \frac{1}{N_f}\sum_m \int_0^{T_f}[h(t) + \delta h(t)]u_m(t)dt.$$

To simplify analysis, $\delta h(t)$ is assumed independent of $u_m(t)$ as adopted in [6]. Then

$$E\{y_n^2\} \approx \frac{1}{N_f^2}\sum_m\Big[\int\int_0^{T_f} h(t)h(\tau)E\{u_m(t)u_m(\tau)\}dtd\tau + \int\int_0^{T_f} E\{\delta h(t)\delta h(\tau)\}E\{u_m(t)u_m(\tau)\}\Big]dtd\tau. \quad (13)$$

To proceed, we apply (8), (9), and (10), to find

$$\begin{aligned} &E\{u_m(t)u_m(\tau)\} \\ &= \frac{1}{N_p^2}\sum_{m'} h(t+(c_m-c_{m'})T_c)h(\tau+(c_m-c_{m'})T_c) \\ &+ \frac{\sigma_v^2}{N_p}\phi(t-\tau) + \sigma_v^2\phi(t-\tau) + \sum_i \frac{\sigma^2_{i,N_p}}{N_p}\cos(2\pi f_i(t-\tau)) \\ &+ \sum_i \mathcal{P}_i E\{g_i^2(t - mT_f - l_m^{(i)}T_i - \epsilon_i)\}\cos(2\pi f_i(t-\tau)) \quad (14) \end{aligned}$$

Substituting (10) and (14) into (13), assuming periodic TH codes, and omitting higher order terms involving $1/N_p^2$, noise plus interference power is approximately

$$\begin{aligned} E\{y_n^2\} \approx\ & \left(\frac{\sigma_v^2}{N_f} + \frac{\sigma_v^2}{N_f N_p}\right)\mathcal{H}_0 + \sum_i\left(\frac{\sigma^2_{i,N_f,n}}{N_f} + \frac{\sigma^2_{i,N_p}}{N_f N_p}\right)\mathcal{G}_{i,0} \\ &+ \frac{1}{N_f N_p}\mathcal{E}_{0,0}^2 + \frac{\sigma_v^2}{N_f N_p}\mathcal{H}_c + \frac{\sigma_v^4}{N_f N_p}\mathcal{Y} \\ &+ \sum_i \frac{\sigma_v^2\sigma^2_{i,N_f,n}}{N_f N_p}\mathcal{X}_i + \sum_i \frac{\sigma^2_{i,N_f,n}}{N_f N_p}\mathcal{G}_{i,c} \\ &+ \sum_{i_1,i_2} \frac{\sigma^2_{i_1,N_p}\sigma^2_{i_2,N_f,n}}{N_f N_p}\mathcal{Z}_{i_1,i_2}. \end{aligned}$$

Here, $\mathcal{Z}_{i_1,i_2}$ is a 2-dimensional integral of cosine functions defined above, which may be evaluated as

$$\mathcal{Z}_{i_1,i_2} = \frac{T_f^2}{2}[\text{sinc}^2(\pi(f_{i_1}-f_{i_2})T_f) + \text{sinc}^2(\pi(f_{i_1}+f_{i_2})T_f)].$$

Since $(f_{i_1} \pm f_{i_2})^2$ is generally very big compared with $1/T_f$, cross terms $\mathcal{Z}_{i_1,i_2}$ for $i_1 \neq i_2$ become negligible, resulting in further simplified noise power

$$\begin{aligned} E\{y_n^2\} \approx\ & \left(\frac{\sigma_v^2}{N_f} + \frac{\sigma_v^2}{N_f N_p}\right)\mathcal{H}_0 + \sum_i\left(\frac{\sigma^2_{i,N_f,n}}{N_f} + \frac{\sigma^2_{i,N_p}}{N_f N_p}\right)\mathcal{G}_{i,0} \\ &+ \frac{1}{N_f N_p}\mathcal{E}_{0,0}^2 + \frac{\sigma_v^2}{N_f N_p}\mathcal{H}_c + \frac{\sigma_v^4}{N_f N_p}\mathcal{Y} \\ &+ \sum_i\left[\frac{\sigma_v^2\sigma^2_{i,N_f,n}}{N_f N_p}\mathcal{X}_i + \frac{\sigma^2_{i,N_f,n}}{N_f N_p}\mathcal{G}_{i,c} + \frac{\sigma^2_{i,N_p}\sigma^2_{i,N_f,n}T_f^2}{2N_f N_p}\right]. \end{aligned}$$

In the limiting case of $N_p \to \infty$, the noise plus interference power can be simplified as

$$E\{y_n^2\} = \frac{\sigma_v^2}{N_f}\mathcal{H}_0 + \sum_i \frac{\sigma^2_{i,N_p}}{N_f}\mathcal{G}_{i,0}.$$

Next we compare our analysis and simulation, and study system performance.

IV. NUMERICAL EXAMPLES

The performance of the MTR receiver in the presence of NBI jamming tones and AWGN is studied with the following parameters: $N_s = 500$, $N_f = 4$, $T_c = 1$ns, $T_f = 20$ns. Simulations are based on the average of 100 independent realizations, using random binary PN sequences, and the channel is generated according to the IEEE UWB channel model CM1 [9]. First, consider both one and two NBI jamming tones. Each NBI signal is assumed to have a symbol rate of one tenth the UWB data rate. Fig. 1 (a) and (b) illustrates both analytical (dashed lines) and simulation (solid lines) waveform estimation MSE for cases of one and two NBI signals, respectively. Analytical MSEs are very consistent with simulation, and show very little degradation for SIRs in the range of 0 to -20dB. However, for SIRs lower than -20dB, MSE performance degrades. Fig. 2 investigates the ratio of frame rate over NBI symbol rate. One NBI signal is adopted in this experiment. It is seen that for SIR above -20dB, MSE is not very sensitive to the ratio, while for SIR under -20dB MSE shows much improvement over the ratio range from 20 to 100. This suggests that it is desirable to adopt higher frame rates for UWB signals to effectively counteract strong NBI. Finally, BER performance is illustrated in Fig. 3, where the analytical value is plotted for the case of two jamming tones as in Fig. 1 (b). BER performance is acceptable up to -20dB SIR, which is partially attributable to acceptable waveform estimation. Further investigation of BER performance and comparison will be conducted in our future work.

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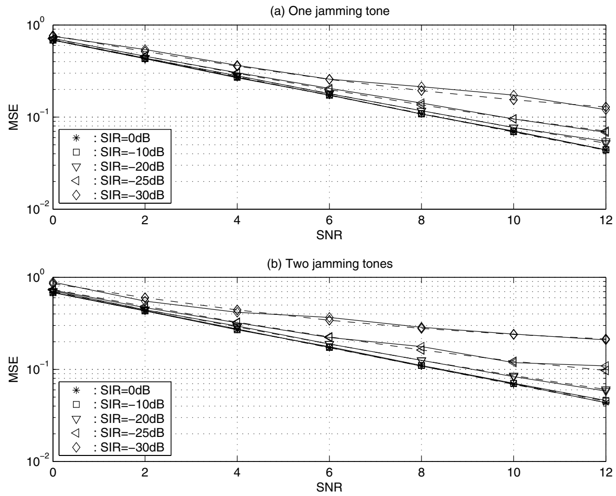

Fig. 1. Effect of SNR and SIR on channel MSE.

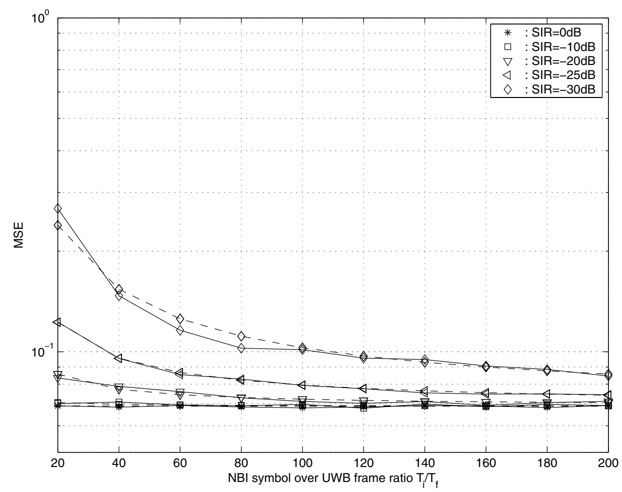

Fig. 2. Effect of UWB frame rate to NBI symbol rate ratio, and SIR, on channel MSE.

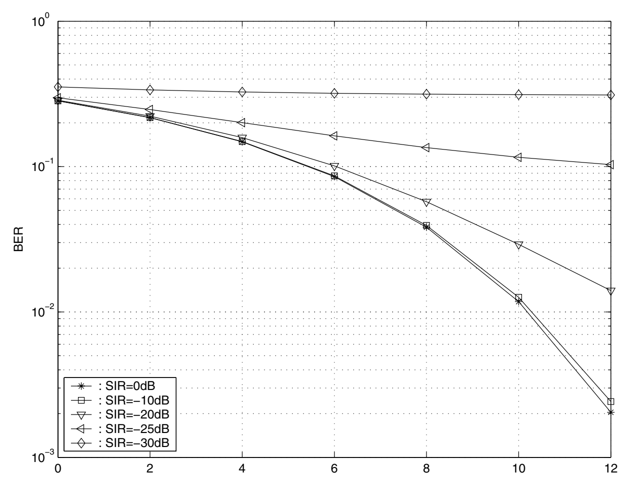

Fig. 3. Effect of SNR and SIR on BER.