Employing Cooperative Diversity for Performance Enhancement in UWB Communication Systems

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***Abstract*— Due to limitation on transmitted power level, any UWB system faces major design challenges in achieving wide coverage while assuring an adequate system performance. In this paper, an employment of cooperative communications in UWB is proposed to enhance the performance and the coverage of UWB by exploiting the broadcasting nature of wireless channels and the cooperation among UWB devices. Symbol-error-rate (SER) performance analysis and optimum power allocation are provided for cooperative UWB multiband OFDM systems with decode-and-forward cooperative protocol. To capture the multipath-clustering phenomenon of UWB channels, the SER performance is characterized in terms of cluster and ray arrival rates. An optimum power allocation is determined based on two different objectives, namely minimizing the overall transmitted power and maximizing the system coverage. Furthermore, an improved cooperative UWB multiband OFDM scheme is proposed to take advantage of unoccupied subbands. Simulation results are shown to validate the theoretical analysis.**

I. INTRODUCTION

Ultra-wideband (UWB) technology shows a great promise for high-speed short-range wireless communications (see [1] and references there in). However, due to the limitation on its transmitted power level, any UWB system faces major design challenges to achieve the desired performance and coverage. To this date, limited works have been proposed to improve the coverage of UWB systems. One approach is by utilizing analog repeaters as used in cellular systems. For example, pulse position modulation UWB repeater was proposed in [2]. Although the analog repeaters are simple, they suffer from noise amplification, which has confined their applications to specific scenarios. Another approach is the employment of multiple-input multiple-output (MIMO) technology in UWB systems. It has been shown that the UWB-MIMO systems can efficiently exploit the available spatial and frequency diversities, and hence greatly improve the UWB performance and coverage range [3], [4]. Nevertheless, it might not be easy to have multiple antennas installed in UWB devices.

Recently, cooperative diversity has emerged as a promising alternative to combat fading in wireless channels. The basic idea is that users or nodes in a wireless network share their information and transmit cooperatively as a virtual antenna array, thus providing diversity that can significantly improve system performance. Various cooperative protocols have been proposed, e.g., amplify-and-forward (AF) protocol [5], decode-and-forward (DF) protocol [5], and user cooperation protocol [6]. In [7], the authors provided symbol-error-rate (SER) performance analysis and optimum power allocation for DF cooperation systems under narrowband Rayleigh fading environment. The research works in [5]-[7] have proved the significant potential of cooperative diversity in wireless networks. Current UWB technology, on the other hand, relies on a non-cooperative transmission, in which the diversity can be obtained only from MIMO coding or information repetition at the transmitter [1]-[4]. Furthermore, many UWB devices are expected to be in home and office environments; most of these devices are not in active mode simultaneously, but they can be utilized as relays to help the active devices. Additionally, due to the TDMA mechanism of the MAC and the network structure of the IEEE 802.15.3a WPAN standard [8], the cooperative protocols can be adopted in UWB WPANs. These facts motivate us to introduce the concept of cooperative diversity in UWB systems as an alternative approach to improve the UWB performance and coverage without the requirement of additional antennas or network infrastructures.

In this paper, we propose to enhance the performance of UWB systems with cooperative protocols. The SER performance analysis and optimum power allocation are provided for cooperative UWB multiband orthogonal frequency division multiplexing (MB-OFDM) systems employing DF cooperative protocol. To capture the clustering property of UWB channels [9], the performance is characterized in terms of the cluster and the ray arrival rates. Moreover, we propose an improved cooperative UWB scheme that is compatible to the current MB-OFDM standard proposal [1]. Both analytical and simulation results show that the proposed cooperative UWB scheme achieves 43% power saving and 85% coverage extension compared with non-cooperative UWB at the same data rate. By allowing both source and relay to transmit simultaneously, the performance of cooperative UWB is further improved to 52% power saving and 100% range extension.

II. SYSTEM MODEL

We consider a UWB MB-OFDM system [1], in which the available spectrum is divided into several subbands. Within each subband, the data is modulated using OFDM technique. Different bit rates are achieved by using different channel coding, frequency spreading, or time spreading rates. The frequency spreading is obtained by choosing conjugate symmetric inputs to the IFFT, while the time spreading is achieved by repeating the same data in an OFDM symbol on two different subbands [1]. The receiver combines the data transmitted via different times or frequencies to increase the signal-to-noise ratio (SNR) of the received signal.

A. Channel Model

As in the IEEE 802.15.3a standard [9], the channel impulse response is based on the Saleh-Valenzuela (S-V) model [10]:

$$h(t) = \sigma^2 \sum_{c=0}^{C} \sum_{l=0}^{L} \alpha(c,l)\delta(t - T(c) - \tau(c,l)), \qquad (1)$$

where σ^2 represents total multipath energy, $\alpha(c,l)$ is the gain of the l^{th} multipath component in the c^{th} cluster, $T(c)$ is the

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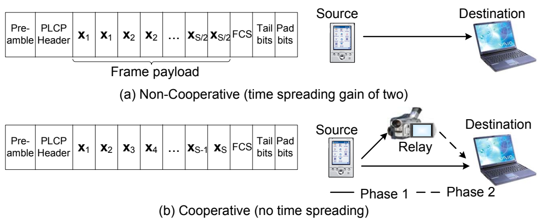

Fig. 1: Illustrations of non-cooperative and cooperative UWB MB-OFDM systems with the same data rate.

delay of the c^{th} cluster, and $\tau(c,l)$ is the delay of the l^{th} path in the c^{th} cluster relative to the cluster arrival time. The cluster arrivals and the path arrivals within each cluster are modeled as Poisson distribution with rate Λ and rate λ (where $\lambda > \Lambda$), respectively. We assume that $\alpha(c,l)$ are modeled as zero-mean, complex Gaussian random variables with variances [9] $\Omega(c,l) = \mathrm{E}\left[|\alpha(c,l)|^2\right] = \Omega(0,0)\exp\left(-\frac{T(c)}{\Gamma} - \frac{\tau(c,l)}{\gamma}\right)$, where $\mathrm{E}[\cdot]$ is the expectation operation, $\Omega(0,0)$ is the mean energy of the first path of the first cluster, Γ is the cluster decay factor, and γ is the ray decay factor. The total energy contained in terms $\alpha(c,l)$ is normalized to unity, i.e., $\sum_{c=0}^{C}\sum_{l=0}^{L}\Omega(c,l) = 1$.

B. Non-Cooperative UWB MB-OFDM System

In a non-cooperative UWB system, each source transmits data directly to its destination. We consider the case when the time-domain spreading with a spreading factor of two is performed, as shown in Fig. 1(a). In Fig. 1, $\mathbf{x}_i$ $(1 \le i \le S)$ denotes a vector of data symbols to be transmitted in each OFDM symbol, and S represents the number of OFDM symbols contained in the frame payload. At the destination, the received signal at the n^{th} subcarrier during the k^{th} OFDM symbol duration is

$$y_{s,d}^k(n) = \sqrt{P_k} H_{s,d}^k(n) x(n) + z_{s,d}^k(n), \tag{2}$$

where P_k is the transmitted power at the source, $x(n)$ denotes a data symbol to be transmitted at subcarrier n, $H_{s,d}^k(n)$ is the frequency response of the channel from the source to the destination, $z_{s,d}^k(n)$ is additive noise, and no intersymbol interference is assumed. The superscript index k, $k = 1$ and 2, is used to distinguish the signals in two consecutive OFDM symbols. Since time spreading is performed, $x(n)$ is the same in both OFDM symbols. The noise, $z_{s,d}^k(n)$, is modeled as a complex Gaussian random variable with zero mean and variance N_0. From (1), the channel frequency response is given by

$$H_{s,d}^k(n) = \sigma_{s,d}^2 \sum_{c=0}^{C}\sum_{l=0}^{L} \alpha_{s,d}^k(c,l) e^{-\mathbf{j}2\pi n \Delta f [T_{s,d}(c) + \tau_{s,d}(c,l)]}, \tag{3}$$

where $\mathbf{j} \triangleq \sqrt{-1}$, $\Delta f = 1/T$, and T is the OFDM symbol period. With an ideal band hopping, we assume that the signal transmitted over different frequency bands undergo independent fading, i.e., $H_{s,d}^k(n)$ are independent for different k. When frequency-domain spreading is performed, the same data can be transmitted in more than one subcarrier. For subsequent performance evaluation, we denote Φ_n as a set of subcarriers that carry the data $x(n)$, and $g_F = |\Phi_n|$ as the frequency spreading gain.

C. Cooperative UWB MB-OFDM Systems

Consider a two-user cooperation over UWB MB-OFDM system. Each user can act as a source or a relay. The cooperation strategy comprises two phases. In Phase 1, the source sends the data to its destination, and the data is also received by the relay. In Phase 2, the source is silent, while the relay helps forward the source data. With the DF cooperative protocol, the relay decodes the received data and forwards it to the destination. We consider the case of no time-domain spreading. In this scenario, the data frame which is transmitted from the source in Phase 1 and from the relay in Phase 2 can be depicted as in Fig. 1(b). We can see from Figs. 1(a) and 1(b) that, for a fixed frequency spreading gain, the cooperative UWB scheme without time spreading achieves the same rate as non-cooperative UWB scheme with time spreading.

In Phase 1, the received signal at the destination is the same as (2) with $k = 1$, and the received signal at the relay is

$$y_{s,r}(n) = \sqrt{P_1} H_{s,r}(n) x(n) + z_{s,r}(n). \tag{4}$$

In Phase 2, the relay forwards the decoded symbol with power P_2 to the destination only if the symbol is decoded correctly; otherwise, the relay does not send or remain idle [7]. The received signal at the destination in Phase 2 is

$$y_{r,d}(n) = \sqrt{\tilde{P}_2} H_{r,d}(n)\ x(n) + z_{r,d}(n), \tag{5}$$

where $\tilde{P}_2 = P_2$ if the relay decodes correctly decodes; otherwise $\tilde{P}_2 = 0$. The channel response $H_{s,r}(n)$ and $H_{r,d}(n)$ also modeled according to the S-V model with total multipath energy $\sigma_{s,r}^2$ and $\sigma_{r,d}^2$. The noise $z_{s,r}(n)$ and $z_{r,d}(n)$ are complex Gaussian distributed with zero mean and variance N_0. We assume that the channel state information is known at the receiver, but not at the transmitter. The channel coefficients are assumed to be independent for different transmit-receive links.

III. SER Analysis for Cooperative UWB MB-OFDM

We analyze the average SER performance of DF cooperative UWB MB-OFDM systems. We focus on the analysis for UWB systems with M-PSK signals as used in [1]. The analysis for M-QAM is similar, and we omit it here due to space limitation.

A. DF Cooperative UWB MB-OFDM

With the knowledge of channel state information, the destination coherently combines the received signals from the source and the relay. Assume that each transmitted symbol has unit energy, then the instantaneous SNR of the maximum ratio combiner (MRC) output can be written as [11]

$$\eta = \frac{P_1}{N_0}\sum_{n\in\Phi_n}|H_{s,d}(n)|^2 + \frac{\tilde{P}_2}{N_0}\sum_{n\in\Phi_n}|H_{r,d}(n)|^2. \tag{6}$$

The conditional SER in case of M-PSK signals is given by [11]

$$\mathrm{P}_e|_{\{H\}} = \Psi(\eta) \triangleq \frac{1}{\pi}\int_0^{f_M}\exp\left(-\frac{b\eta}{\sin^2\theta}\right)d\theta, \tag{7}$$

where $b = \sin^2(\pi/M)$. From (4) and (7), the instantaneous SNR at the MRC output of the relay is $\eta_{s,r} = \frac{P_1}{N_0}\sum_{n\in\Phi_n}|H_{s,r}(n)|^2$, and the conditional probability of incorrect decoding at the relay is $\Psi(\eta_{s,r})$. Taking into account the two possible cases of $\tilde{P}_2$, the conditional SER in (7) can be re-expressed as

$$\mathrm{P}_e|_{\{H\}} = \Psi(\eta)|_{\tilde{P}_2=0}\Psi(\eta_{s,r}) + \Psi(\eta)|_{\tilde{P}_2=P_2}\left[1-\Psi(\eta_{s,r})\right]. \tag{8}$$

Substitute (6) into (8) and average over the channel realizations, resulting in the average SER

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$$\mathrm{P}_e = \frac{1}{\pi}\int_0^{f_M} \mathcal{M}_{\eta_{s,d}}(b_\theta)\mathcal{M}_{\eta_{r,d}}(b_\theta)d\theta\Big[1-\frac{1}{\pi}\int_0^{f_M}\mathcal{M}_{\eta_{s,r}}(b_\theta)d\theta\Big] + \frac{1}{\pi^2}\int_0^{f_M}\mathcal{M}_{\eta_{s,d}}(b_\theta)d\theta\int_0^{f_M}\mathcal{M}_{\eta_{s,r}}(b_\theta)d\theta, \quad (9)$$

where $f_M = \pi - \pi/M$, $b_\theta = \frac{b}{\sin^2\theta}$, $\eta_{s,d} = \frac{P_1}{N_0}\sum_{n\in\Phi_n}|H_{s,d}(n)|^2$, $\eta_{r,d} = \frac{P_2}{N_0}\sum_{n\in\Phi_n}|H_{r,d}(n)|^2$, and $\mathcal{M}_\eta(s) = \mathrm{E}[\exp(-s\eta)]$ is the moment generating function (MGF) of η [11]. Observe that the MGFs of $\eta_{s,d}$, $\eta_{s,r}$ and $\eta_{r,d}$, are in terms of the multipath coefficients whose amplitudes are Rayleigh distributed, as well as the multipath delays which are based on Poisson process. In general, it is difficult, if not impossible, to obtain closed-form formulations of the MGFs in (9). In this case, we exploit an approach in [12] which allows us to approximate $\mathcal{M}_{\eta_{x,y}}(s)$ as

$$\mathcal{M}_{\eta_{x,y}}(s) \approx \prod_{n=1}^{g_F}\Big(1+\frac{sP_x\sigma_{x,y}^2\beta_n(\mathbf{R}_{x,y})}{N_0}\Big)^{-1}, \quad (10)$$

where $P_x = P_1$ if x is the source and $P_x = P_2$ if x is the relay. In (10), $\beta_n(\mathbf{R}_{x,y})$ denotes the eigenvalues of a matrix $\mathbf{R}_{x,y}$, which is a correlation matrix whose each diagonal component is one and the $(i,j)^{th}$ $(i \neq j)$ component is given by

$$\mathbf{R}_{x,y}(i,j) = \Omega_{x,y}(0,0)Q_{i,j}(\Lambda_{x,y},\Gamma_{x,y}^{-1})Q_{x,y}(\lambda_{x,y},\gamma_{x,y}^{-1}), \quad (11)$$

where $Q_{i,j}(a,b) = (a+b+\mathbf{j}2\pi(n_i-n_j)\Delta f)/(b+\mathbf{j}2\pi(n_p-n_q)\Delta f)$, in which n_i denotes the i^{th} element in the set Φ_n. Note that the MGF in (10) is exact if $g_F = 1$ ($\Phi_n = \{n\}$). By substituting (10) into (9), we get the average SER performance

$$\mathrm{P}_e \approx F[U_{s,d}(\theta)U_{r,d}(\theta)](1-F[U_{s,d}(\theta)]) + F[U_{s,d}(\theta)]F[U_{s,r}(\theta)] \quad (12)$$

where $U_{x,y}(\theta) = \prod_{n=1}^{g_F}\big(1+\frac{v_{x,y}(n)}{\sin^2\theta}\big)$, $F[x(\theta)] = \frac{1}{\pi}\int_0^{f_M}\frac{1}{x(\theta)}d\theta$, and $v_{x,y}(n) = bP_x\sigma_{x,y}^2\beta_n(\mathbf{R}_{x,y})/N_0$.

To get more insights of the cooperative UWB performance, we also provide approximate SER formulations that involve no integration as follows. By removing the negative term in (12) and bounding $1+v_{x,y}(n)/\sin^2\theta$ with $(1+v_{x,y}(n))/\sin^2\theta$, we get

$$\mathrm{P}_e \approx \prod_{n=1}^{g_F}(1+v_{s,d}(n))[A_{2g_F}(1+v_{r,d}(n)) + A_{g_F}^2(1+v_{s,r}(n))], \quad (13)$$

where $A_i = \frac{1}{\pi}\int_0^{f_M}\sin^{2i}\theta d\theta$. If all channel links are available, i.e., $\sigma_{s,d}^2 \neq 0$, $\sigma_{s,r}^2 \neq 0$, and $\sigma_{r,d}^2 \neq 0$, the SER of cooperative UWB scheme can be further approximated by ignoring all 1's in (13) as

$$\mathrm{P}_e \approx \prod_{n=1}^{g_F} v_{s,d}(n)[A_{2g_F}v_{r,d}(n) + A_{g_F}^2 v_{s,r}(n)]. \quad (14)$$

In Fig. 2, we compare the above SER approximations with SER simulation curves in case of cooperative UWB system with frequency spreading gains $g_F = 1$ and 2. The simulated MB-OFDM system has $N = 128$ subcarriers, the subband bandwidth is 528 MHz, and the channel model (CM) parameters follow those for CM 1 [9]. For fair comparison, we plot average SER curves as functions of P/N_0. Clearly, the theoretical SER (12) closely matches with the simulation curves. The SER approximations (13) are close to the simulation curves for the entire SNR range, while the SER approximations (14) are loose at low SNR but they are tight at high SNR.

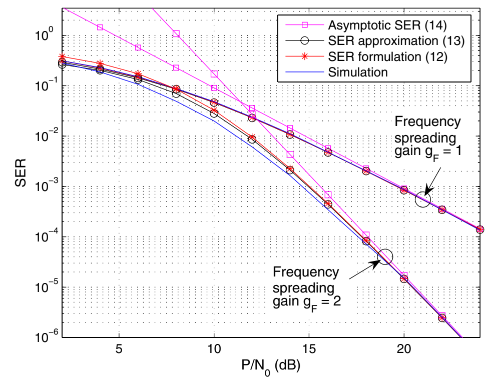

Fig. 2: Comparison of SER formulations and simulation results for the DF cooperative UWB system: $\sigma_{s,d}^2 = \sigma_{s,r}^2 = \sigma_{r,d}^2 = 1$, $P_1 = P_2 = P/2$.

B. Comparison of Cooperative and Non-Cooperative UWB

We compare here the performance of cooperative and non-cooperative UWB MB-OFDM systems with the same data rate. Due to space limitation, we focus on the case of frequency spreading gains $g_F = 1$ and 2. Assuming equal power allocation ($P_1 = P_2 = P/2$ as in [1]), the performance of non-cooperative UWB system with time spreading gain of two can be evaluated as $P_e = (G_{NC}P/N_0)^{-2g_F}$, i.e., the diversity gain is twice the frequency spreading gain. The coding gain is $G_{NC} = b\sigma_{s,d}^2/(2\sqrt{A_2})$ if $g_F = 1$ and $G_{NC} = b\sigma_{s,d}^2\sqrt{1-B_{s,d}^2}/(2A_4^{\frac{1}{4}})$ if $g_F = 2$. Here, $B_{x,y}$ is related to the channel model parameters as

$$B_{x,y} = \Omega_{x,y}(0,0)\frac{\big[(\Lambda_{x,y}+\Gamma_{x,y}^{-1})^2+q\big]^{\frac{1}{2}}\big[(\lambda_{x,y}+\gamma_{x,y}^{-1})^2+q\big]^{\frac{1}{2}}}{\big[(\Gamma_{x,y}^{-1})^2+q\big]^{\frac{1}{2}}\big[(\gamma_{x,y}^{-1})^2+q\big]^{\frac{1}{2}}},$$

in which $q = (2\pi\mu\Delta f)^2$ and μ denotes the subcarrier separation. For cooperative scheme, let us denote $r = P_1/P$ as the power ratio of the transmitted power P_1 at the source over the total power P. According to (14), the approximate SER of DF cooperative UWB system can be expressed as

$$P_e \approx (G_{DF}P/N_0)^{-2g_F}, \quad (15)$$

i.e., the cooperative UWB scheme achieve the same diversity gain as the non-cooperative scheme. The factor G_{DF} represents cooperation gain which can be determined as $G_{DF} = b\sigma_{s,d}\sigma_{s,r}\sigma_{r,d}r/[A_1^2\sigma_{r,d}^2 + A_2\sigma_{s,r}^2 r/(1-r)]^{1/2}$ if $g_F = 1$ and $G_{DF} = b\sigma_{s,d}\sigma_{s,r}\sigma_{r,d}r[(1-B_{s,d}^2)(1-B_{s,r}^2)(1-B_{r,d}^2)]^{\frac{1}{4}}/[A_2^2\sigma_{r,d}^2(1-B_{r,d}^2) + A_4\sigma_{s,r}^2(1-B_{s,r}^2)r^2/(1-r)^2]^{\frac{1}{4}}$, if $g_F = 2$. Since both non-cooperative and cooperative UWB systems achieve the same diversity order, it is interesting to compare the coding gain and the cooperation gain. The ratio $\xi = G_{DF}/G_{NC}$ in case of $g_F = 1$ and 2 are

$$\xi = V\left(A_1^2/A_2\sigma_{r,d}^2 + r/(1-r)\sigma_{s,r}^2\right)^{-\frac{1}{2}}; \quad (16)$$

$$\xi = V\left(\frac{A_2^2(1-B_{s,d}^2)\sigma_{r,d}^2}{A_4(1-B_{s,r}^2)} + \frac{r^2(1-B_{s,d}^2)\sigma_{s,r}^2}{(1-r)^2(1-B_{r,d}^2)}\right)^{-\frac{1}{4}}, \quad (17)$$

respectively, where $V = 2r\sigma_{s,r}\sigma_{r,d}/\sigma_{s,d}$.

IV. Optimum Power Allocation

We provide an optimum power allocation for cooperative UWB MB-OFDM system with two different objectives, namely mini-

TABLE I: Comparisons of optimum power allocation obtained via exhaustive search and analytical results: $\sigma_{s,d}^2 = 1$, CM 1, $\varepsilon = 5 \times 10^{-2}$.

$\sigma_{s,r}^2$	$\sigma_{r,d}^2$	g_F	Search	From (13)	From (19)
10	1	1	0.5321	0.5356	0.5247
10	1	2	0.5072	0.5095	0.5023
1	10	1	0.7873	0.7772	0.7968
1	10	2	0.8082	0.7882	0.8316

mizing overall transmitted power and maximizing the coverage.

A. Power Minimization using Cooperative Communications

We define $\mathbf{P} = [P_1 \ P_2]^T$ as a power allocation vector. Our objective is to minimize the overall transmitted power under the constraint on the SER performance and the transmitted power level. The optimization problem is formulated as

$$\min_{\mathbf{P}} \quad P = \sum_i P_i \tag{18}$$
$$\text{s.t.} \begin{cases} \text{Performance: } \mathrm{P}_e \le \varepsilon; \\ \text{Power: } P_i \le \bar{P}, \ \forall i, \end{cases}$$

where ε denotes the required SER and $\bar{P}$ is the maximum transmitted power for each subcarrier. The first constraint in (18) is to ensure the performance requirement. The second constraint is related to the limitation on the transmitted power level.

Consider at first the formulated problem in (18) without the maximum power constraint. Using the SER in (14), the optimum power allocation can be determined, after some manipulations, as

$$P_1 = rP \text{ and } P_2 = (1-r)P, \tag{19}$$

where in case of $g_F = 1$:

$$P = N_0/(V\sqrt{\varepsilon})\left(A_2 r/(1-r)\sigma_{s,r}^2 + A_1^2\sigma_{r,d}^2\right)^{1/2}, \tag{20}$$
$$r = (\sigma_{s,r} + K)(3\sigma_{s,r} + K)^{-1}, \tag{21}$$

in which $K = \sqrt{\sigma_{s,r}^2 + (8A_1^2/A_2)\sigma_{r,d}^2}$, and in case of $g_F = 2$:

$$P = \frac{N_0}{V}\Big(\frac{A_4 r^2\sigma_{s,r}^4(1-B_{s,r}^2) + A_2^2(1-r)^2\sigma_{r,d}^4(1-B_{r,d}^2)}{\varepsilon(1-r)^2(1-B_{s,d}^2)(1-B_{s,r}^2)(1-B_{r,d}^2)}\Big)^{1/4},$$
$$r = \frac{4^{\frac{1}{3}}c^2 + 2(c_{s,r} + 3c_{r,d})c + 4^{\frac{2}{3}}(c_{s,r}^2 - 12c_{s,r}c_{r,d})}{6(2c_{s,r} + c_{r,d})c}, \tag{22}$$

in which $c = \left[3(2c_{s,r} + c_{r,d})(12c_{s,r}c_{r,d} + 81c_{r,d}^2)^{1/2} + 2c_{s,r}^2 + 72c_{s,r}c_{r,d} - 27c_{r,d}^2\right]^{1/3}$, $c_{s,r} = A_4\sigma_{s,r}^4(1 - B_{s,r}^2)$ and $c_{r,d} = 2A_2^2\sigma_{r,d}^4(1 - B_{r,d}^2)$. The results in (21) and (22) reveal that the asymptotic power allocation of cooperative UWB systems depends only on the quality of source-relay link and relay-destination link, but not the source-destination link. In case of jointly encoded across subcarriers, the optimum power allocation also depends on the multipath clustering property of UWB channels through parameters $B_{x,y}$. Table I shows that the optimum power allocation obtained from (19) and that based on SER in (13) agree with that obtained via exhaustive search to minimize (12) for all considered scenarios. According to the SER expressions in Section III-B, the ratio between the power of cooperative and non-cooperative UWB systems with the same spreading gain is

$$\frac{P_{DF}}{P_{NC}} = \frac{N_0 P_e^{-1/(2g_F)}G_{DF}^{-1}}{N_0 P_e^{-1/(2g_F)}G_{NC}^{-1}} = \frac{G_{NC}}{G_{DF}} = \frac{1}{\xi}. \tag{23}$$

Substituting power allocation in (21), (22) into (23), we can show that if source-relay link is of high quality (e.g. $\sigma_{s,d}^2 = \sigma_{r,d}^2 = 1$, $\sigma_{s,r}^2 = 10$), then cooperative scheme yields about 50% power saving compared to non-cooperative scheme with the same rate; if relay-destination link is of high quality (e.g. $\sigma_{s,d}^2 = \sigma_{s,r}^2 = 1$, $\sigma_{r,d}^2 = 10$), the power saving of 80% can be achieved.

With the maximum power limitation, it is difficult to obtain a closed form solution to the problem in (18). In this case, we provide a solution as follows. Let P_1 and P_2 be the transmitted powers that are obtain by solving (18) without the maximum power constraint, and let $\hat{P}_1$ and $\hat{P}_2$ denote our solution.

- If $\min\{P_1, P_2\} > \bar{P}$, then no feasible solution to (18).
- Else if $\max\{P_1, P_2\} \le \bar{P}$, then $\hat{P}_1 = P_1$ and $\hat{P}_2 = P_2$;
- Otherwise, (i) Let $j = \arg\max_i\{P_1, P_2\}$ and $j' = \arg\min_i\{P_1, P_2\}$. (ii) Set $P_j = \bar{P}$ and find $P_{j'}$ such that the desired SER performance is satisfied, i.e., $P_{j'}$ is obtained by solving $\mathrm{P}_e - \varepsilon = 0$ where P_e is according to (13) or (14) with P_j replaced by $\bar{P}$. (iii) If $P_{j'} \le \bar{P}$, then $\hat{P}_j = \bar{P}$ and $\hat{P}_{j'} = P_{j'}$; Otherwise, no feasible solution to (18).

B. Coverage Enhancement using Cooperative Communications

We determine the optimum power allocation and the relay location so as to maximize the distance between the source and the destination with constraint on the error performance. The geometry on the channel link qualities is taken into account by assuming that the total multipath energy $\sigma_{x,y}^2$ is modeled as

$$\sigma_{x,y}^2 = \kappa \ D_{x,y}^{-\nu}, \tag{24}$$

where κ is a constant whose value depends on the propagation environment, ν is the propagation loss factor, and $D_{x,y}$ represents the distance between node x and node y. Given a fixed total transmitted power P, we aim to jointly determine power allocation $r = P_1/P$ and relay location to maximize the distance $D_{s,d}$. Based on the SER performance obtained in the previous section, we can see that the performance of cooperative UWB system is related not only to the power allocation but also the location of the nodes. Obviously, the optimum relay location must be on the line joining the source and the destination. In this case, the distance $D_{s,d}$ can be written as a summation of the distance of the source-relay link and relay-destination link, i.e., $D_{s,d} = D_{s,r} + D_{r,d}$. Now, we formulate an optimization problem as follows:

$$\max_{r, D_{s,r}, D_{r,d}} \quad D_{s,r} + D_{r,d} \tag{25}$$
$$\text{s.t.} \begin{cases} \text{Performance: } \mathrm{P}_e \le \varepsilon; \\ \text{Power: } rP \le \bar{P}, \ (1-r)P \le \bar{P}, \ 0 < r < 1. \end{cases}$$

With the SER formulations derived in Section III, Lagrange multiplier method can be apply to solve (25) without maximum power constraint, and then a similar solution to the discussion at the end of Section IV-A can be employed to obtain the solution under the maximum power constraint. We omit the analysis here due to space limitation.

Table II shows the optimum power allocation and the distances obtained via exhaustive search (using the SER in (12)) and that from analytical solutions (using SER in (13)). Clearly both results match closely. Interestingly, when P/N_0 is small, the maximum coverage is achieved when the relay is located far away from the source, and almost all of the transmitted power P is allocated at the source. On the other hand, when P/N_0 is high ($P/N_0 > 30$

TABLE II: Power allocation, relay location, and maximum coverage of cooperative UWB MB-OFDM systems.

P/N_0	Exhaustive Search			Analytical Solution		
(dB)	r	$D_{s,r}$	$D_{s,d}$	r	$D_{s,r}$	$D_{s,d}$
25	0.86	13.00	14.06	0.88	13.74	14.87
35	0.55	15.53	33.82	0.58	15.12	33.98
25	0.89	17.11	19.14	0.88	17.31	19.79
35	0.52	13.21	43.87	0.54	13.27	43.92

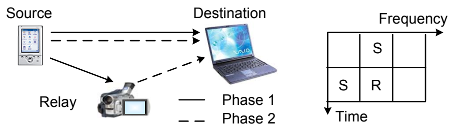

Fig. 3: Illustration of an improved cooperative UWB MB-OFDM.

dB), the optimum relay location is about the midpoint between source and destination, and the power should be equally allocate at the source and the relay. The reason behind this is that, at small SNR, the transmitted power is not large enough for the cooperation system to achieve the performance of diversity order two, hence the forwarding role of the relay is less important and almost all of the power should be used at the source. At high enough SNR, the diversity order of two can be achieved, so the relay should be in the middle to balance the channel quality of source-relay link and relay-destination link.

V. Improved Cooperative UWB MB-OFDM

The current multiband standard proposal [1] allows several UWB devices to transmit at the same time using different subbands. However, in a short-range scenario, the number of UWB devices that simultaneously transmit their information tend to be smaller than the number of available subbands. In this section, we propose an improved cooperative UWB strategy that makes use of the unoccupied subbands as follows. Let the time-domain spreading with spreading factor of two is performed at the source. The improved cooperative UWB scheme comprises two phases, each corresponding to one OFDM symbol period. In Phase 1, the source broadcasts its information using one subband. In Phase 2, the source repeats the information using another subband to gain the diversity from time spreading, while the relay forwards the source information using an unoccupied subband. The destination combines the received signals from the source directly in Phase 1 and Phase 2, and the signal from the relay in Phase 2. Fig. 3 illustrates an example of the improved cooperative UWB system. In Fig. 3, the source and the relay are denoted respectively by S and R. It is worth noting that the improved cooperative UWB scheme is compatible with the current multiband standard proposal [1] which allows multiuser transmission using different subbands. In addition, the proposed scheme yields the same data rate as the non-cooperative scheme with the same spreading gain.

Let P_1 and P_2 denote the transmitted power at the source in Phase 1 and Phase 2, and let P_3 denotes the power at the relay. Following the same procedures as in Section III, the SER of the improved cooperative UWB scheme can be approximated as

$$\mathrm{P}_e \approx F[U_{s,d}^2(\theta)U_{r,d}(\theta)](1 - F[U_{s,d}(\theta)]) + F[U_{s,d}^2(\theta)]F[U_{s,r}(\theta)],$$

in which the asymptotic performance can be determined as

$$P_e \approx (G_I P/N_0)^{-3g_F}, \tag{26}$$

where $G_I = W/[A_1 A_2 \sigma_{r,d}^2 + A_3 \sigma_{s,r}^2 r_1/r_3]^{\frac{1}{3}}$ if $g_F = 1$, and $G_I = WZ/[A_2 A_4 \sigma_{r,d}^4 (1 - B_{r,d}^2) + A_6 \sigma_{s,r}^4 (1 - B_{s,r}^2) r_1^2/r_3^2]^{\frac{1}{6}}$ if $g_F = 2$, in which $W = b[\sigma_{s,d}^4 \sigma_{s,r}^2 \sigma_{r,d}^2 r_1^2 r_2]^{\frac{1}{3}}$ and $Z = [(1 - B_{s,d}^2)^2 (1 - B_{s,r}^2)(1 - B_{r,d}^2)]^{\frac{1}{6}}$. That is the improved cooperative UWB system provides an overall performance of diversity order $3g_F$. Based on the above SER formulations, the optimum power allocation can be determined in a similar way as in Section IV.

VI. Simulation Results

We perform computer simulations to compare the performance of the proposed cooperative UWB schemes and to validate the derived theoretical results. In all simulations, we consider UWB MB-OFDM system with 128 subcarriers, the signal is based on QPSK, and the subband bandwidth of 528 MHz. The propagation loss factor is $\nu = 2$. The source is located at position (0, 0).

In Fig. 4, we compare the average SER performances of UWB systems with different cooperation strategies. The locations of the relay and the destination are (1m, 0) and (2m, 0). All channel links are modeled by CM 1. Equally power allocation is used. For fair comparison, we present the SER curves as functions of P/N_0. We can see from Fig. 4 that both non-cooperative and cooperative UWB systems achieve an overall performance of diversity order $2g_F$. In case of $g_F = 1$, the cooperative UWB scheme outperforms the non-cooperative UWB by 2 dB at a SER of 10^{-3}. This agrees with the analysis in (16) which shows that the performance gain of the DF cooperative UWB compared with the non-cooperative UWB is $\xi = [(1 + A_1^2/A_2)\sigma_{s,d}^2]^{1/2} = 1.59$. In case of $g_F = 2$, the performance of cooperative scheme is about 2.5 dB better than that of non-cooperative scheme. This also corresponds to the analysis in (17) in which the performance gain is $\xi = [(1 + A_2^2/A_4)\sigma_{s,d}^2]^{1/4} = 1.81$. Additionally, Fig. 4 illustrates that the improved cooperative UWB scheme provides the performance of diversity order $3g_F$ and yields about 2 dB performance improvement over the cooperative UWB scheme.

Figs. 5 and 6 compare the total transmitted power of non-cooperation and cooperation systems to achieve the same range. The performance requirement is $P_e \leq 5 \times 10^{-2}$. The relay is located in the middle between the source and the destination ($D_{s,d} = D_{s,r}/2$). All channel links are modeled by CM 4. In Fig. 5, we consider the case of no limitation on the transmitted power level. By increasing the frequency spreading gain, the overall transmitted power can be reduced by 60%. With the same g_F, the cooperative scheme achieves 43% power saving compared to the non-cooperative scheme. This is in consistent with the analytical results in (23), in which the power ratio of cooperative and non-cooperative scheme can be calculated as $P_{DF}/P_{NC} = 0.59$ in case of $g_F = 1$ and $P_{DF}/P_{NC} = 0.54$ in case of $g_F = 2$. Fig. 5 also shows that using the improved cooperative UWB scheme can achieve up to 52% power saving compared to the non-cooperative scheme. In Fig. 6, the maximum power constraint is taken into account, and the power is allocated according to the suboptimal solution provided in Section IV-A. The power limitation is set at $P_i/N_0 \leq 19$ dB. The tendencies observed in Fig. 6 are similar to those in Fig. 5. The improve cooperative scheme saves about 50% overall transmitted power in case of $g_F = 1$ and saves about 20% in case of $g_F = 2$.

Next, we study the coverage of UWB system under different cooperation strategies. All channel links are based on CM 4. The SER performance requirement is fixed at 5×10^{-2}. In Fig. 7, we depicts the coverage as a function of P/N_0. The transmitted

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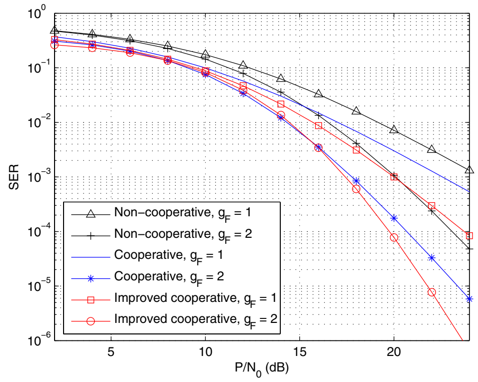

Fig. 4: SER performance vs. P/N_0.

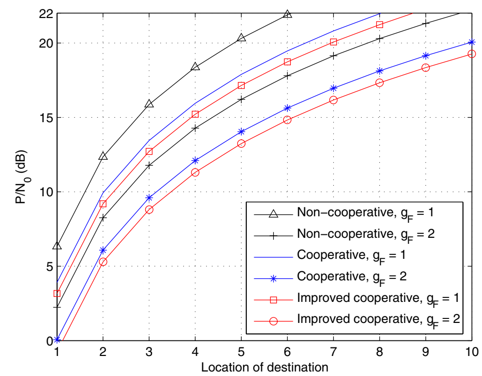

Fig. 6: P/N_0 vs. destination location (with power limitation).

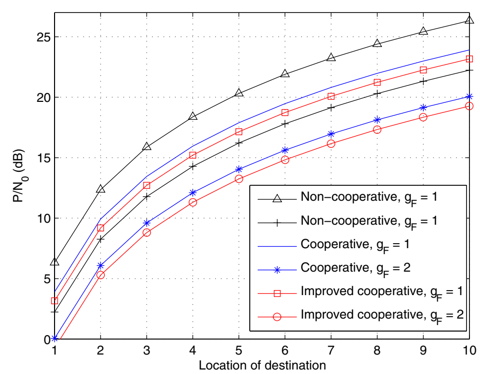

Fig. 5: P/N_0 vs. destination location (no power limitation).

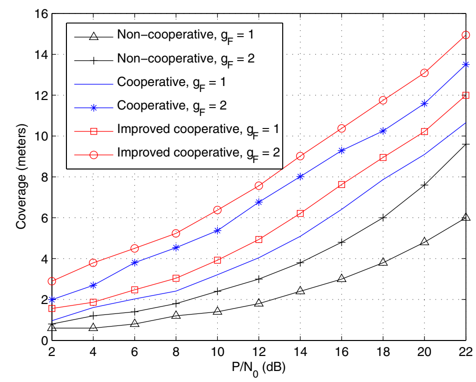

Fig. 7: $D_{s,d}$ vs. P/N_0 (with power limitation).

power level is limited by $P_i/N_0 \leq 19$ dB. For cooperative scheme, the relay location and the power allocation are designed such that the distance $D_{s,d}$ is maximized. With the same P/N_0 and the same transmission data rate, the coverage of UWB system can be increased by 85% using the cooperative scheme, and it can be increased by 100% using the improved cooperative scheme.

VII. Conclusions

We propose to enhance the performance of UWB systems by employing cooperative diversity. We analyze the SER performance and provide optimum power allocation of cooperative UWB MB-OFDM systems with decode-and-forward protocol. Both non-cooperative and cooperative schemes achieve the same diversity order of twice the frequency spreading gain for every channel environment. The cooperation gain, on the other hand, depends on the clustering property of UWB channels. By taking advantage of the relay location and properly allocating the transmitted power, the cooperation gain can be improved such that the cooperative UWB achieves superior performance to the non-cooperative scheme with the same data rate. It turns out that at low SNR, the coverage is maximized if the relay is located farthest away from the source, and almost all of the transmitted power is allocated at the source; at high SNR, the coverage is maximized if the relay is located in the midpoint between source and destination, and equal power allocation is used. We also propose to further improve the cooperative UWB scheme by allowing the source and the relay nodes to simultaneously retransmit the information. Simulation results confirm the theoretical analysis that the cooperative UWB scheme can achieve 43% power saving and 85% coverage extension compared to the non-cooperative scheme, while the improved cooperative UWB scheme can achieve 52% power saving and 100% coverage extension.

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