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Multi-Carrier Ultra-Wideband Multiple-Access with Good Resilience against Multiuser Interference

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Abstract — **We propose a multi-carrier based multiple-access scheme for ultra-wideband (UWB) communications that is capable of deterministic removal of multiuser interference, irrespective of the users' multipath channels, in asynchronous mode. The receivers for different users have the same structure, except for a different mixer front-end. The maximum-likelihood receiver can be matched-filter based, with only the desired user's channel state information, and hence without the need for multiuser detection. Performance simulation shows significant improvement as compared with existing time-hopping spread spectrum UWB multiple access schemes.**

Keywords: ultra-wideband, multiple-access, multiuser interference, multicarrier

I. Introduction

Ultra-Wideband (UWB) communication using impulse radio has many attractive features for short-range high-rate wireless applications and has attracted much research and industrial attention recently; see e.g., [6,9,12]. For multiuser communications, time-hopping (TH) based pseudo-random spread spectrum multiple access has been introduced in [5, 10], which relies on the statistical properties of the TH spreading codes and the random channel for user separation, and the multiuser interference (MUI) is treated as additive noise.

For TH UWB system using random TH sequences, a multiuser detector needs to know all the users' channel state information (CSI), just like in a direct-sequence code division multiple access (DS-CDMA) system. This poses great difficulty to the receiver design. Also, multiuser detectors usually have high complexity: linear detectors such as decorrelating and minimum mean-squared error (MMSE) detectors need matrix inversion whenever channel changes (except in slowly varying channels with adaptive algorithms), while the optimum maximum-likelihood (ML) detection entails exponential complexity. Sphere decoding can provide near-ML performance but still has high complexity (polynomial of order 3 to 6 in number of users) [1,3]. There is therefore a need to reduce the MUI and remove it completely if possible.

Deterministic user separation for multiple access has been proposed before for narrow-band (as opposed to UWB) systems in [2] and later extended and generalized in [7] and [13]. Recently, a UWB multiple access scheme that is capable of deterministic user separation has been proposed [12], based on digital block spreading and ideas in [13]. The scheme in [12] can guarantee MUI elimination irrespective of the multipath channels. But there are two restrictions on the system in [12]: i) quasi-synchronism among the users needs to be maintained, which requires coordination/cooperation among the users; and ii) the multipath channels' delay spread is limited to a design parameter. In this paper we propose a multicarrier-based multiple access scheme that can achieve the same goals as those in [12] in terms of deterministic user separation, but without these two restrictions. The disadvantage, as compared with [12] is that the proposed system will have (slightly) lower bandwidth efficiency. But this should not be a significant issue because in UWB, the available bandwidth is abundant.

We will establish the system model in Section II and describe the receiver design in Section III. We will simulate the performance in terms of probability of error of the proposed system in Section IV and conclude the paper in Section V.

II. System Model

Suppose a multiuser asynchronous communication system with M users, all transmitting at the same symbol rate one symbol per T_s seconds. We suppose for simplicity that all the users use the same modulation scheme, pulse amplitude modulation (PAM). Other modulation schemes are also possible. However, unless a carrier is introduced, the modulation scheme should be real (as opposed to complex).

We next describe the modulation for one arbitrary, say the mth user. Using PAM, the mth user's transmitted signal can be written as

$$x_m(t) = \sum_{n=-\infty}^{\infty} s_{mn} p_m(t - nT_s), \qquad (1)$$

where s_{mn} is the nth PAM symbol of the mth user, $p_m(t)$ is the mth user's spectral shaping pulse, which depends on m.

Assume that s_{mn} is an independent and identically distributed (i.i.d.) sequence with zero mean. The power spectrum of $x_m(t)$ is then given by

$$\Phi_{xx}(f) = \frac{\sigma^2_{s,m}}{T_s} |P_m(f)|^2, \qquad (2)$$

where $\sigma_{s,m}^2$ is the variance of $s_{m,n}$, and $P_m(f)$ is the Fourier transform of $p_m(t)$. We use the following definition of Fourier transform $X(f)$ of a function $x(t)$: $X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt$.

The received multiple-access signal can be written as

$$y(t) = \sum_{m=1}^{M} x_m(t) \star h_m(t) + n(t), \qquad (3)$$

where $\star$ denotes convolution and $h_m(t)$ is the m-th user's channel, and $n(t)$ is the additive noise. We model the users' channels as linear time-invariant; slowly time-varying channels can also be incorporated.

A Shift Orthogonality and Frequency Division

Our goal is to design a multiple access scheme that can be eventually MUI-free, irrespective of the asynchronous multipath channels of the users. Ideally, we would want the signals from different users to be orthogonal even after their respective multipath propagation. This, however, requires that the spectral shaping pulses used by different users to be orthogonal, *and* that shifted versions of them also orthogonal, for any shift amount. Specifically, we need that

$$p_m(t) \perp p_k(t-\tau), \quad \forall m, k \in [1, M], \forall \tau, \qquad (4)$$

where $a(t) \perp b(t)$ if and only if $\int_{-\infty}^{\infty} a(t)b(t)dt = 0$. We may call the condition in (4) *shift-orthogonality* [4,8].

A little thinking reveals that such shift-orthogonality is only possible if the spectra of $p_m(t)$ and $p_n(t)$ do not overlap. To be exact, they should overlap almost nowhere — the Lebesgue measure of their overlap should be zero. To see this we can use the Parseval equality (inner product in time domain equals the inner product in frequency-domain) of the Fourier transform and translate the conditions in (4) to the following equivalent one

$$\int_{-\infty}^{\infty} P_m(f)P_k(f)e^{-j2\pi f\tau}df = 0, \, \forall m, k \in [1, M], \forall \tau, \quad (5)$$

which means that the inverse Fourier transform of $P_m(f)P_k(f)$ is the zero signal. Therefore, $P_m(f)P_k(f)$ should also be zero, almost everywhere. We summarize it in the following proposition.

Proposition 1 *Two signals are shift orthogonal, if and only if their spectral supports do not overlap.*

Proposition 1 means that in order to make the users' signals orthogonal to each other after arbitrary multipath propagation, the users' transmitted signals need to occupy different frequency bands — their spectra should not overlap. This indicates that our goal of channel-irrespective orthogonality-based MUI removal can only be achieved if we use some frequency-division schemes. Intuitively, this is also very natural: the users' signals, viewed in the frequency-domain, will be subject to different frequency responses and if they do not overlap at the transmission side, they will also not overlap at the receiver side (assuming that the channels are linear). Orthogonality is preserved in the frequency-domain. This is to be contrasted with most DS-CDMA systems, in which the orthogonality between the users' spreading codes can be easily lost after multipath propagation.

B Multicarrier UWB Multipath Access

To allocate different frequency bands to different users, we can simply do it in a frequency-division multiple access (FDMA) way, that is, allocate a consecutive frequency band to each user. Such allocation, however, is not preferred. For, we want to spread the spectrum of one user as widely as possible so that the multipath diversity (or frequency-selectivity) can be sufficiently utilized. We therefore propose to allocate the frequencies to the users in an interleaved (but still non-overlapping) manner. To that goal, we next describe how $p_m(t)$ is generated.

Let $g(t)$ denote a *monocycle* [9] pulse, which is the shortest pulse unit to be transmitted; the duration of a monocycle pulse is usually shorter than one nanosecond. We denote the (approximate) duration of $g(t)$ by T_g; the bandwidth of the Fourier transform $G(f)$ of $g(t)$ is approximately $1/T_g$. Let $w(t)$ be a windowing function, common to all users, which has its (approximate) time duration equal to the symbol duration T_s, much larger than T_g. One example of the window function is the rectangular function

$$w(t) = \begin{cases} 1, & |t| \leq T_s/2 \\ 0, & \text{otherwise.} \end{cases} \qquad (6)$$

The approximate bandwidth of the Fourier $W(f)$ of $w(t)$ is $1/T_s$. With f_m denoting a user-specific "carrier" frequency, the spectral shaping pulse $p_m(t)$ can be written as

$$p_m(t) = \sum_{i=-\infty}^{\infty} g(t - iT_c)w(t)\cos(2\pi f_m t), \qquad (7)$$

where T_c is a parameter that satisfies $T_g \leq T_c \leq T_s$; subscript c stands for "chip", similar to a chip in a DS-CDMA system, except that here the chip duration is larger than the chip pulse support.

To describe the multicarrier nature of the spectrum and the reason for MUI resilience, we examine the Fourier transform $P_m(f)$ in the next, which will also reveal the roles played by the different parameters of the system T_s, T_c, T_g, etc.

Using basic convolution and modulation properties of Fourier transform, we can express $P_m(f)$ as follows

$$P_m(f) = \frac{1}{2T_c} \sum_{i=-\infty}^{\infty} G\left(\frac{i}{T_c}\right) \cdot \left[W(f + f_m - \frac{i}{T_c}) + W(f - f_m - \frac{i}{T_c}) \right] \qquad (8)$$

That is, the spectral shaping pulse has a spectrum that is periodically shifted and scaled pairs (the $\pm f_m$ terms) of

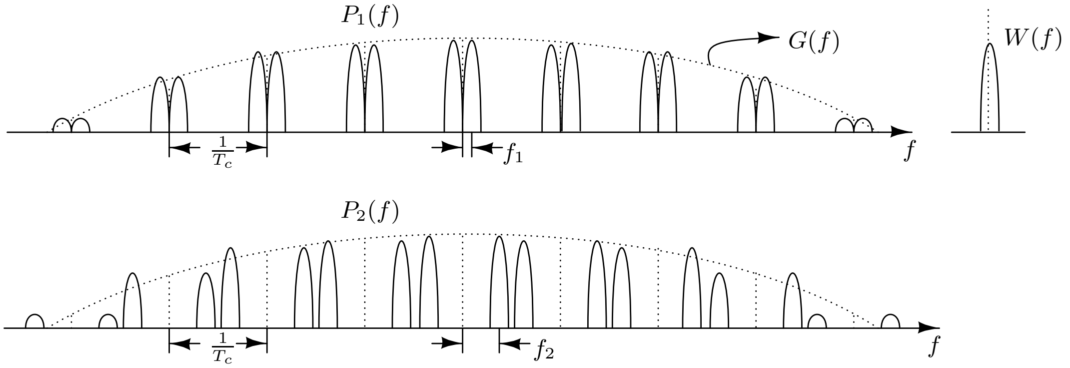

Figure 1: An example of the spectral-shaping pulses $P_1(f)$ and $P_2(f)$ for a system of two users

the baseband windowing spectrum $W(f)$. The frequencies $\{f_m\}$ are chosen such that the spectra of different users do not overlap: the users are separated in the frequency domain. In general, $0 \leq f_m \leq 1/T_c$.

To give an illustrative example, we show in Fig. 1 the spectra $P_1(f)$ and $P_2(f)$ for a system with two users. In the example, $G(i/T_c)$ is zero for $|i| > 4$, $W(f)$ has small support, and f_1 and f_2 are chosen such that the support for $P_1(f)$ and $P_2(f)$ do not overlap.

We explain next the different roles played by the functions and parameters:

i) The mono-cycle pulse $g(t)$ controls the spectral width of the system. The narrower it is, the wider the spectrum of the system. The presence of $g(t)$ essentially distinguishes UWB system from other (narrowband or wideband) systems. Although UWB can be viewed as a spread spectrum system with a large spreading factor mathematically, it is unique as a practical system in its extreme wide bandwidth and use of ultra-narrow pulses.

ii) The window function $w(t)$ determines the building component (spikes in Fig. 1) in the transmitted spectra for the users. In practice, we want $W(f)$ to have tight spectral support and fast decaying factor in the frequency domain, so as to reduce the inter-user interference. Theoretically speaking, if $W(f)$ has finite frequency support (e.g., as does the raised cosine function), then we can achieve perfect separation of the users in the presence of the multipath.

iii) The parameter T_c is critical in the trade-off of the maximum number of supportable users $M_{\max}$ and the *processing gain* $\mathcal{G}$ (in the spread spectrum communication sense) per user. Specifically, the maximum number users supportable without multi-user interference is (roughly) given by

$$M_{\max} = T_s/(2T_c), \tag{9}$$

which is the number of copies of $W(f)$ that we can fit within a bandwidth of $1/(2T_c)$ (cf. Fig. 1). If we let $1/T_g$ denote roughly the bandwidth of $G(f)$, we have about

$$\mathcal{G} = 2T_c/T_g, \tag{10}$$

copies of $W(f)$ per user, which is approximately the processing gain per user. Obviously, the product $M_{\max} \cdot \mathcal{G}$ is a constant for fixed T_g and T_s. The trade-off between the number of users and the spreading or processing gain per user is therefore governed by the proper choice of T_c.

T_g	monocycle pulse width
$1/T_g$	system bandwidth
T_c	chip duration
T_s	symbol duration
$T_s/(2T_c)$	max. number of users
$2T_c/T_g$	spreading gain per user

Table 1: Major Parameters of the Proposed scheme

We summarize the major parameters of the system in Table 1 and the result about the MUI-free multiple access scheme as follows.

Proposition 2 *For a given mono-cycle pulse $g(t)$ with spectral width $1/T_g$ and a common user rate $1/T_s$ symbols per second, it is possible to design an asynchronous UWB multiple access (uplink) or broadcasting (downlink) system with no multi-user interference for M users, each with processing gain $\mathcal{G}$, irrespective the multiple multipath channels experienced by different users, provided that $M \cdot \mathcal{G} \leq T_s/T_g$. The spectral shaping pulses for different users can be designed according to* (7) *with appropriately chosen parameters T_c and f_m, $m \in [1, M]$.*

For an example system with $M = 6$ users, $T_g = 1$ns, and $G = 4$, we plot in Fig. 2 the time-domain signals of the spectral-shaping pulses $p_m(t)$, $m = 1, \ldots, 6$. The window function $w(t)$ is chosen to be a raised-cosine pulse with roll-off factor 1. Notice that the envelope of the shaping pulses is the raised-cosine waveform. Also, the monocycles within one symbol interval have different amplitudes. In other words, the users' transmissions are not constant modulus. This can be partially corrected by selecting a flatter window function $w(t)$ such as a rectangular function (6), which does not have finite spectral support, however, and hence can cause multi-user interference. Even if a rectangular function $w(t)$ is chosen, the transmissions are still non-constant modulus due

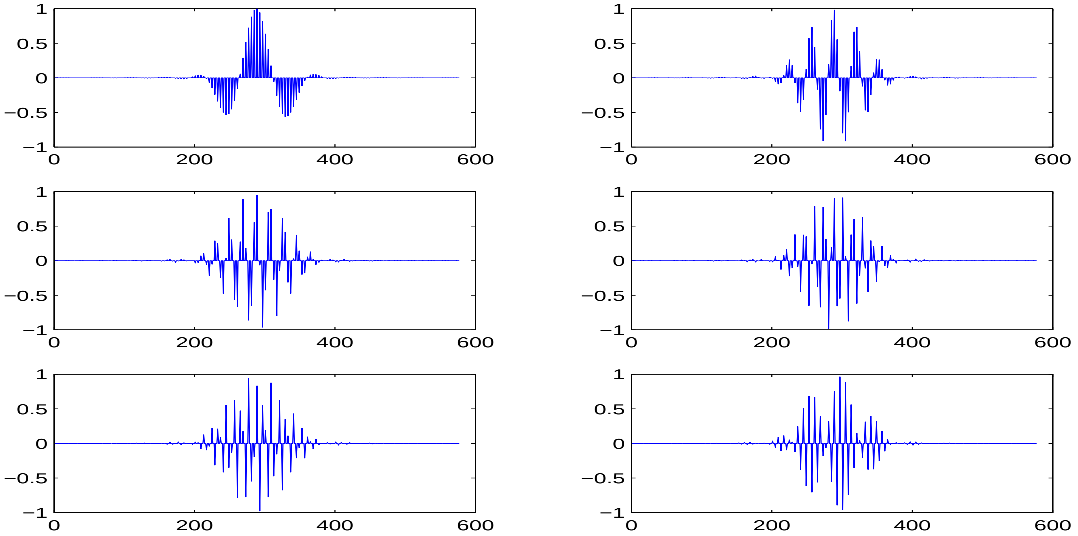

Figure 2: The spectral shaping pulses for an example system of $M = 6$ users. The time is given in nano-seconds.

to the presence of the $\cos(2\pi f_m t)$ "carrier" term in (7). The peak-to-average power ratio (PAPR) in this case is 3 dB (equal to the PAPR of a cosine function). The non-constant-modulus problem of the proposed scheme is not as pronounced as the PAPR problem in orthogonal frequency-division multiplexing (OFDM). The reason is that in UWB, the power level of the individual pulses are usually kept low and the power amplifiers therefore can work in their linear regions. The total energy per information symbol is accumulated by transmitting many low-power impulses (monocycles).

Notice that a digital chip-interleaved block spreading (CIBS) multiple access scheme for UWB that is also capable of perfect user separation in the presence of multipath has been designed in [12]. Our scheme is different in the following aspects:

1. The system in [12] requires quasi-synchronism among the users; our scheme can operate in a fully asynchronous mode.
2. For fixed system parameters, there is a limit on maximum delay spread on the multipath channels in [12]. Here we do not have this constraint.

Despite the differences, both [12] and the scheme we propose can suppress MUI deterministically, rather than relying on the statistical MUI suppression and multi-user detection at the receiver. As a result, our system shares the superior performance of that in [12], as compared to the previous MUI-present TH based impulse radio multiple-access (IRMA) designs in e.g., [5, 10, 11].

III. Receiver Design

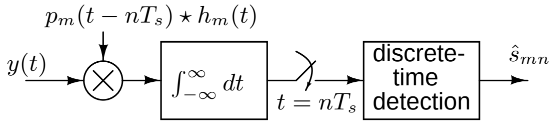

Figure 3: The single-user optimum receiver

Since the users' signals remain orthogonal after propagating through the multipath channels, we can use correlator based (or matched filter based) single-user receivers to detect the users' signals at the receiver (see Fig. 3). To produce a set of sufficient statistics for the detection of the mth user's symbols, we only need to pass the received signal $y(t)$ through a single-user matched filter that is matched to the convolution of the mth user's transmit pulse $p_m(t)$ and the mth user's channel $h_m(t)$, and sample; the samples so obtained are sufficient for the optimum (e.g., ML) detection of the mth user's symbols. No information about other users' channel is needed, as the projection of the received signal onto other users' signal spaces generates only irrelevant statistics. We assume that the users' channels have been estimated. Channel estimation is an interesting problem for UWB, but it will not be addressed in this work.

Thanks to the similarity in the spectral shaping pulses for different users, their receiver structures can also be made similar. Specifically, all the users' receiver can be made the same as shown in Fig. 4 with the help of a comb filter, except for a user-specific front-end, which is a mixer with the user-specific $\cos(2\pi f_m t)$ as one input.

IV. Performance Simulation

To demonstrate the performance of the proposed system, we compare the Bit Error Rate (BER) of 2-PAM modulated multiple access using the proposed scheme with a TH multiple-access scheme as given in [10]. Both system employ a matched filter (RAKE) receiver. There are $M = 32$ users in the system and the processing gain per user is $\mathcal{G} = 20$; $T_g = 1$ns. Each user's channel is modeled as independent, having 100 equally spaced i.i.d. complex Gaussian distributed taps with 1ns between two consecutive taps. The delay spread is assumed to be much

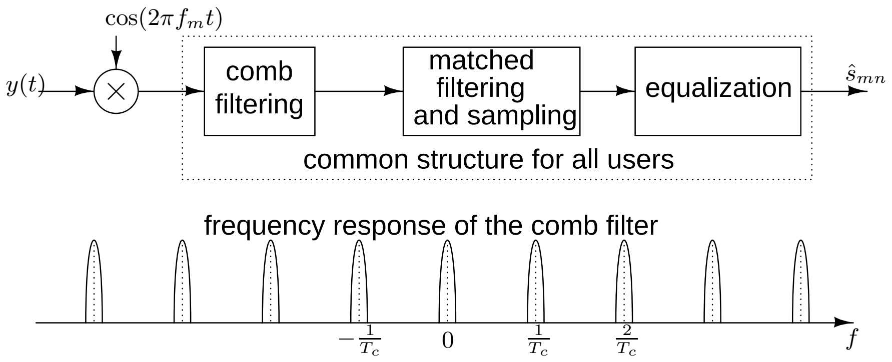

Figure 4: The receiver structure for the mth user, with a user-specific front end

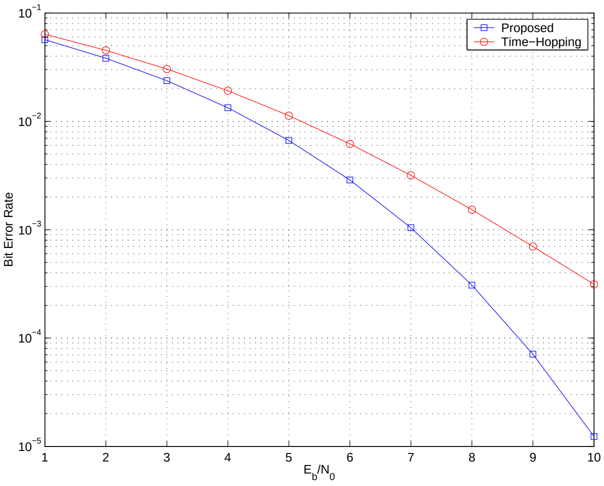

Figure 5: BER comparison of the proposed scheme with existing time-hopping spread spectrum multiple access

smaller that the symbol duration T_s so that the intersymbol interference can be ignored. The performance comparison is reported in Fig. 5 for average BER over sufficiently many realizations of the multipath channels. As we can see, the proposed scheme has clearly an advantage in performance, thanks to its user separation capability.

V. Conclusions

We proposed a multicarrier multiple access scheme for ultra-wideband communications that can preserve the orthogonality among the users' signals even after multipath propagations. The system can operate in full asynchronous mode. At the receiver, the optimum detector can be based on a single-user matched filter front end, and requires no knowledge of channel state information of users other than the one desired. The system is flexible in terms of balancing between the number of users and the processing gain per user. Simulation results demonstrated performance advantage over existing time-hopping multiple access schemes previously proposed for ultra-wideband communications. We have considered only pulse amplitude modulation in this paper, but other modulation schemes such as pulse position modulation, frequency modulation, and orthogonal signaling can also be used. Future work will include analytical performance evaluation and low-complexity receiver designs.

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