ORTHOGONAL TRANSMULTIPLEXER: A MULTIUSER COMMUNICATIONS PLATFORM FROM FDMA TO CDMA

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ABSTRACT

Orthogonal transmultiplexers have been successfully utilized for multi-user communications. They are of the FDMA type in their most common version. Mostly, frequency-selective PR-QMFs were used in transmultiplexers as orthogonal user codes for CDMA communications reported in the literature. This conflicts with the fundamentals of CDMA theory. We introduce novel M-valued spread spectrum PR-QMF codes in this paper. It is shown that the proposed M-valued spread spectrum PR-QMF codes with minimized auto- and cross-correlation properties outperform the conventional Gold codes in CDMA communication scenarios considered in the paper.

I. INTRODUCTION

The theory of filter banks and subband transforms has been widely utilized for spectral analysis and synthesis applications in many engineering disciplines. The synthesis/ analysis orthogonal filter bank configuration serves as a multiplexing and demultiplexing tool for time-domain (TDM) to frequency domain (FDM) conversions. TDM to FDM and FDM to TDM conversions have been used in single, discrete multitone (DMT) and multi-user communications.

In its most popular version, an orthogonal transmultiplexer utilizes a set of frequency selective functions or filters to accommodate the communications needs of many users over a single channel. Therefore, each user is assigned a frequency localized carrier, or bandwidth, using a dedicated fraction of channel spectrum.

In contrast, a unit sample function of certain phase is assigned as the user code for the TDM case. In this case, a time slot is dedicated for a user implying the availability of full channel spectrum.

The code division multiple access (CDMA) scheme has been forwarded as an alternative to the classical TDM and FDM methods. More recently, orthogonal transmultiplexers were proposed for spread spectrum CDMA communications [1][2][3]. The CDMA schemes provide a user with the whole frequency and time slots of a communications channel. Therefore, the user codes are to be spread both in the time and frequency domains [4]. The optimality measures of these codes in the context of orthogonal transmultiplexers are discussed and a design methodology is suggested in this paper. The correlation properties and CDMA communications performance of the proposed spread spectrum PR-QMF codes are compared with those of the conventional Gold codes [5][6]. It is shown that the first outperforms the latter under the test scenarios considered in this study.

II. THE PR-QMF BANK AS AN ORTHOGONAL TRANSMULTIPLEXER

II.A M-BAND CASE:

A maximally decimated M-band FIR PR-QMF bank structure is displayed in Fig. 1. A perfect reconstruction (PR) filter bank is one where the output is simply a delayed version of the input, i.e.

$$y(n) = x(n-n_0) \tag{1}$$

where n_0 is a delay constant related to the filter duration. A *paraunitary* (or PR-QMF) filter bank satisfies the PR requirement [7]. In this solution, the synthesis filters $\{g_k(n)\}$ are time-reversed versions of the analysis filters $\{h_k(n)\}$, that is

$$g_k(n) = h_k(r-n). \tag{2}$$

Hence, we can state the necessary and sufficient conditions of a paraunitary filter bank on the analysis filters. These conditions are summarized in the time domain as [7]

$$\sum_k h_r(k)h_r(k+Mn) = \delta(n) \tag{3a}$$

$$\sum_k h_r(k)h_s(k+Mn) = 0 \quad , \quad \forall n \tag{3b}$$

Eq. (3a) implies that such impulse response $h_r(n)$ is normalized to unit energy $\sum |h_r(n)|^2 = 1$, and is orthogonal to its translates shifted by M. Eq. (3b) implies that $\{h_r(k)\}$ is orthogonal to $\{h_s(k)\}$, and to all M translates of $\{h_s(k)\}$. The detailed treatment of these perfect reconstruction filter banks can be found in references [7][8][9].

II.B TWO-BAND/USER CASE:

The PR-QMF conditions for a two-band filter bank are summarized as

$$\sum_n h(n)h(n+2k) = \delta(k) \tag{4}$$

where $h(n) = h_0(n)$ is the prototype low-pass PR-QMF.

It is observed from Eqs. (3) and (4) that there are infinitely many PR-QMFs available in the solutions space. This point was recognized and optimal PR-QMF design measures and procedures were proposed earlier in the literature [7]. These design measures basically manipulate the time and frequency domain properties of the filter functions. Therefore, they help us to find the PR-QMF solutions among all solutions which best fit the requirements of the application under study.

The conventional orthogonal digital transmultiplexer is an FDMA type multiuser communications system. Therefore, the synthesis and analysis functions, $\{g_i(n)\}$ and $\{h_i(n)\}$, respectively, are frequency selective (The conventional filter banks with good frequency characteristics are the proper choice for this purpose). The available channel bandwidth is allocated among the users. Therefore, a user is assigned a dedicated band or subchannel for its use. This is naturally the counterpart of the TDMA system which provides dedicated time slots for the communications of the users.

This communications scenario (synthesis/analysis configuration) is also used for orthogonal frequency division modulation (OFDM) or discrete multitone (DMT) in the literature. DMT has been proposed as a standard for high-speed digital subscriber line (HDSL) and asymmetric digital subscriber line (ADSL) communications [10].

On the other hand, in a TDM system dedicated time slots providing for interleaving of signals is obtained by upsampling followed by filters $G_0(z) = 1$, and $G_1(z) = z^{-1}$. These filters are time-localized, $g_0(n) = \delta_n$, and $g_1(n) = \delta_{n-1}$ whose orthogonality is evident in the time domain. Furthermore since $|G_0(e^{j\omega}| = |G_1(e^{j\omega})| = 1$, they are also all-pass filters. The TDM signals occupy the entire frequency band, but are interleaved or *localized* in time.

The CDMA design approach in this paper seeks to distribute the orthogonality properties over both time and frequency domains.

III. OPTIMAL DESIGN OF SPREAD SPECTRUM PR-QMF CODES FOR CDMA TRANSMULTIPLEXER

Recent advances in wireless and mobile radio communications suggests CDMA as a potential alternative to the existing TDMA-based systems. All users of a CDMA system are equally entitled to use any time and frequency slots. This implies that the user codes are spread both in time and frequency domains. Therefore, CDMA is theoretically advantageous to the conventional multiplexing techniques like TDMA and FDMA which localize in either the time or frequency domain, respectively. The PR-QMF based CDMA schemes proposed earlier in the literature are basically an FDMA (or frequency hopping) system since they use frequency selective PR-QMFs as their user codes. The desired user codes of an orthogonal transmultiplexer for CDMA communications should jointly satisfy the following time-frequency conditions

(a) The orthogonal user codes can not be unit sample functions in the time domain. This prevents CDMA from becoming a TDMA scheme.

(b) The orthogonal user codes should be all-pass like spread spectrum functions with minimized inter- and intra-code correlations. This condition assures that the communications scheme can not become an FDMA type.

The spread spectrum properties of CDMA communications are preserved in this non-conventional PR-QMF based orthogonal transmultiplexer scheme.

III.A OPTIMAL DESIGN CRITERIA

In addition to the PR-QMF constraints given in Eq. (3), the following correlation and time-frequency properties of the user codes are included as metrics in the objective function to be optimized

(a) Minimization of the inter- and intra-code correlations

$$R_{00}(k) = \sum_k h_0(n)h_0(n+k) \qquad (k > 0, k \in Z) \quad (5)$$

$$R_{01}(k) = \sum_k h_0(n)h_1(n+k) \qquad (\forall k, k \in Z) \quad (6)$$

(b) Spreading the PR-QMF codes in both frequency and time domains as evenly as possible. This point is critical for PR-QMF codes in CDMA communications. This contrasts with the conventional PR-QMFs which approximate the ideal brick-wall frequency responses. The frequency selectivity of conventional PR-QMFs (FDM) diminish with this consideration and they become orthogonal spread spectrum codes of the desired CDMA type.

The time spread of a discrete-time function $\{h_0(n)\}$ is defined by [7][9]

$$\sigma_n^2 = \frac{1}{E}\sum_n (n-\bar{n})^2 |h_0(n)|^2, \qquad (7)$$

The energy, E, and time center, $\bar{n}$, of the function $\{h_0(n)\}$ are

$$E = \sum_n |h_0(n)|^2 \qquad (8)$$

$$\bar{n} = \frac{1}{E}\sum_n n|h_0(n)|^2. \qquad (9)$$

Similarly, the frequency spread is defined as

$$\sigma_\omega^2 = \frac{1}{2\pi E}\int_{-\pi}^{\pi} (\omega-\bar{\omega})^2 |H_0(e^{j\omega})|^2 d\omega, \qquad (10)$$

where

$$H_0(e^{j\omega}) = \sum_n h_0(n)e^{-j\omega n}$$

$$\bar{\omega} = \frac{1}{2\pi E}\int_{-\pi}^{\pi} \omega |H_0(e^{j\omega})|^2 d\omega. \qquad (11)$$

Therefore, we can set the objective function to be optimized as

$$\{J\}_{max} = \alpha\sigma_n^2 + \beta\sigma_\omega^2 - \gamma\sum_k |R_{00}(k)| - \eta\sum_k |R_{01}(k)| \quad (12)$$

subject to the paraunitary PR constraint $\sum_n h(n)h(n+2k) = \delta(k)$, and where $R_{00}(k)$ and $R_{01}(k)$ were defined in Eqs. (5) and (6), respectively. Fig. 2 compares the spectra of a 32-length spread spectrum PR-QMF code for the two-user case optimized for $\alpha = 0$, $\beta = 0$, $\gamma = 1$, $\eta = 1$ with a 31-length Gold code [6]. parameters $\{\alpha, \beta, \gamma, \eta\}$ can be changed in order to emphasize the corresponding metrics of the objective function. Fig. 3 displays the time-frequency localizations of the proposed spread spectrum PR-QMF code solutions along with the conventional PR-QMFs. This figure demonstrates the marked departure of the spread spectrum PR-QMF codes from the conventional ones. Therefore, one can obtain the optimal solution for the stated purpose from among infinitely many functions in the space. In the next section, we will compare the communications performance of the 32-length spread spectrum PR-QMF and 31-length Gold codes.

IV. PERFORMANCE COMPARISON OF SPREAD SPECTRUM PR-QMF AND GOLD CODES IN CDMA COMMUNICATIONS

The bit error rate (BER) performance results of a CDMA communication system based on a two-user orthogonal transmultiplexer are presented and compared in this section for both 32-length spread spectrum PR-QMF and 31-length Gold code-based codes. We consider BPSK modulation and antipodal signaling for a CDMA system with signals transmitted over an additive white Gaussian noise (AWGN) channel. Since multiple users transmit in the same time and frequency slots, multiple-access interference (MAI) is introduced.

The asynchronous communication scenario is tested for both spread spectrum user codes. M-ary spread spectrum PR-QMF codes have better auto-correlation (AC) and cross-correlation (CC) properties than Gold codes. At least half of the AC and CC values are automatically forced to be zero in M-ary spread spectrum PR-QMF codes because of the perfect reconstruction properties, as given in Eq.3. The other half of the AC and CC terms of the user codes are minimized in the optimization step. The system is observed for a single block time (bit period) in the simulations. The asynchronous transmissions from the other users are randomly shifted with a fraction of the bit period. For signal-to-multi-user interference power (SIR) level of $0dB$, multiple computer runs are performed in order to simulate the asynchronous communications scenario. Then, the results are smoothed by time averaging. The BER performance results are displayed in Fig. 4.

It is found from performance simulations that the proposed M-ary spread spectrum PR-QMF codes outperform the well-known Gold codes under the same test conditions. The implementation issues of the proposed family of M-ary multiuser codes are currently being studied.

V. CONCLUSIONS

Orthogonal PR-QMF based transmultiplexers have been proposed for CDMA communications in the literature. Frequency -selective conventional PR-QMFs were used in most of the earlier studies (FDMA). We propose nonconventional M-ary spread spectrum PR-QMF codes with minimized auto- and cross-correlation properties in this letter. The proposed orthogonal user codes are entirely different from the conventional PR-QMFs. The superior performance of the M-ary spread spectrum PR-QMF codes over the conventional Gold codes in CDMA communications is presented. It is expected that M-ary spread spectrum PR-QMF codes designed under practical considerations might find their CDMA applications in the future.

References

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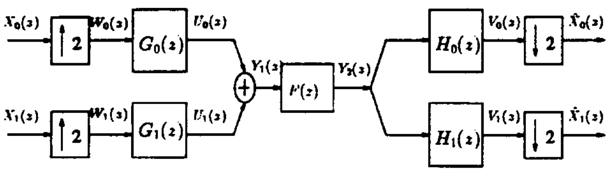


Figure 1: Two-band transmultiplexer structure.

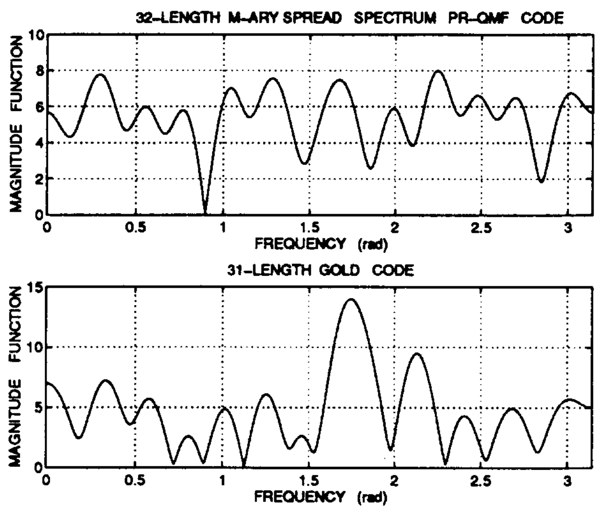
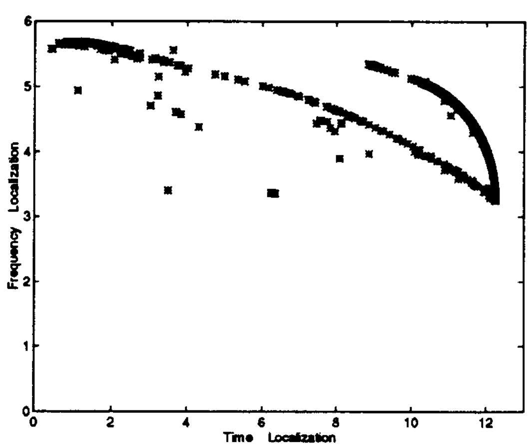
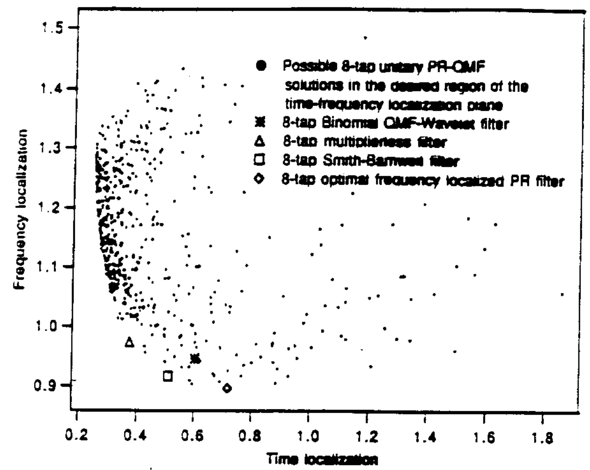


Figure 2: Frequency spectra of 32-length M-ary spread spectrum PR-QMF and 31-length Gold codes.



(a)



(b)

Figure 3: (a) Time-frequency localizations of the proposed two-user M-ary spread spectrum PR-QMF codes for 8-tap case, b) Time-frequency localizations of the conventional two-band PR-QMFs for 8-tap case.

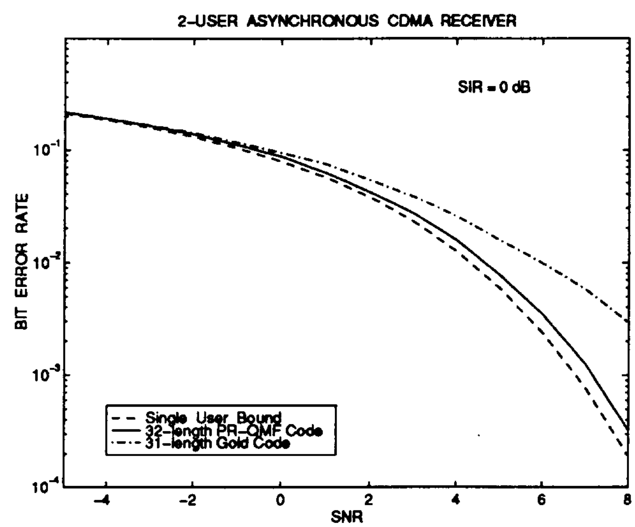


Figure 4: BER performance of two-user asynchronous CDMA system for different user code types with $SIR = 0dB$.