A novel Radon-based multi-carrier direct sequence code division multiple access transceiver design and simulation

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Abstract: Multi-carrier direct sequence code division multiple access (MC-DS-CDMA) has emerged recently as a promising candidate for the next generation broadband mobile networks. Multipath fading channels have a severe effect on the performance of wireless communication systems even those systems that exhibit efficient bandwidth, like orthogonal frequency division multiplexing (OFDM) and MC-DS-CDMA; there is always a need for developments in the realisation of these systems as well as efficient channel estimation and equalisation methods to enable these systems to reach their maximum performance. A novel MC-DS-CDMA transceiver based on the Radon-based OFDM, which was recently proposed as a new technique in the realisation of OFDM systems, will be used here as a basic building block in the design of MC-DS-CDMA transceiver to increase the orthogonality against the multipath frequency selective fading channels. Simulation results are provided to demonstrate the significant gains in performance and simplicity due to the proposed techniques.

Keywords: multi-carrier; MC; finite Radon transform; FRAT; multi-carrier direct sequence code division multiple access; MC-DS-CDMA; Radon-based OFDM.

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1 Introduction

Direct sequence spread spectrum transmission has received considerable attention for applications in mobile and personal communications networks as a result of its potential to provide higher spectral efficiencies in comparison to conventional modulation schemes (Gilhousen et al., 1990; Pickholtz et al., 1991).

Recently, a number of multi-carrier code division multiple access (MC-CDMA) systems have been proposed (DaSilva and Sousa, 1994; Vandendorpe, 1995; Sourour and Nakagawa, 1996; Hara and Prasad, 1997). Among these systems, multi-carrier direct sequence code division multiple access (MC-DS-CDMA) combines time domain spreading and multi-carrier (MC) modulation. An interesting property of MC-DS-CDMA systems is that the available channel bandwidth is divided into a set of equal width subchannels, and narrowband CDMA waveforms are transmitted over the subchannels. Due to this configuration, MC-DS-CDMA system is capable of supporting high data rate services over hostile radio channels. Another interesting property of MC-DS-CDMA systems is that the modulation and demodulation can be implemented using fast Fourier transform (FFT). Another advantage of MC-DS-CDMA system is its desirable capability of narrowband suppression. It has been shown in Kondo and Milstein (1996) that the MC-DS-CDMA systems are ingenious in suppressing narrowband interference (NBI) via frequency diversity. MC-DS-CDMA systems are known to be effective in frequency selective fading channels (Namgoong et al., 2000). As other MC-CDMA systems, the performance of MC-DS-CDMA system degrades mainly due to the multiple access interference (MAI) (Hara and Prasad, 2003).

The effect of a carrier frequency offset on the performance of MC-DS-CDMA was considered in Steendam and Moeneclaey (2001). And the effect of chip waveform shaping on the performance of MC-CDMA systems was studied in Nguyen (2005). In Yang and Hanzo (2002) and Yu et al. (2006), the performance of generalised MC-DS-CDMA over fading channels was studied.

The Radon transform was first introduced by Radon (1917) (Natterer, 1986), and the theory, basic aspects and applications of this transform are studied in Deans (1983) and Bolker (1987), while the finite Radon transform (FRAT) was first studied by Beylkin (1987). Most of the researches that employ the Radon transform are mainly concerned in the image processing field and especially in the image authentication and image denoising (Do and Vetterli, 2003). In this paper, Radon transform is used as a main building block in a proposed novel MC-DS-CDMA transceiver which uses the recently proposed one-dimensional (ID) serial Radon-based orthogonal frequency division multiplexing (OFDM) (Al-Jawhar et al., 2008; Kattoush et al., 2008).

2 Radon transform, inverse Radon transform and FRAT

Let (x, y) designate coordinates of points in the Cartesian plane and consider some arbitrary function f defined on some domain D on R^2. If L is any line in the plane, then the mapping defined by the projection or line integral of f along all the possible lines L is the [two-dimensional (2D)] Radon transform of f provided that the integral exists.

Explicitly,

$$\breve{f} = Rf = \int_L f(x, y)ds \tag{1}$$

where ds is an increment of length along L. The domain D may include the entire plane or some region of the plane.

The mapping defined by equation (1) along with its inverse and certain generalisations, was studied first by Radon (1917) (Do and Vetterli, 2003; Natterer, 1986). Radon showed that if f is continuous, then Rf is uniquely determined by integrating along all the lines L.

There are many approaches to recover function f from its RT version $\breve{f}$ (Deans, 1983; Do and Veterli, 2003); Fourier transform (FT) method of inverse Radon transform (IRT) will be used through out this paper. The fundamental connection between FT and RT is established through the following equation (Deans, 1983):

$$\tilde{f} = F_1\breve{f} = F_1 Rf \tag{2}$$

where F_1 is the ID FT and $\tilde{f}$ is the FT of f function.

In effect, $\breve{f}$ maybe obtained by applying the inverse FT in the radial direction once $\tilde{f}$ is known. Symbolically,

$$Rf = F^{-1}F_n f \tag{3}$$

Thus, given $\breve{f}$, it is possible to recover f by a radial FT followed by n-dimensional inverse FT. Symbolically,

$$f = F_n^{-1} F_1 \breve{f} \tag{4}$$

FRAT was defined for 2D images in Bolker (1987), Hanzo et al. (2003) and Yen and Hanzo (2001). In this paper, the FT approach will be used due to its suitability for our purposes. The FRAT of a 2D matrix A can be obtained first by taking the 2D-FFT of A (Bolker, 1987; Natterer, 1986):

$$F(r, s) = \sum_{m=0}^{p-1} \sum_{n=0}^{p-1} A(m, n) e^{-j(2\pi/p)rm} e^{-j(2\pi/p)ns} \tag{5}$$

Then, the order of coefficients in the corresponding Fourier slices are controlled by the direction of a set of normal vectors, namely (a_k, b_k), where k = 0, 1, 2, … , p. These normal vectors refer to the row and column indices in the Fourier domain. The optimal ordering of Radon coefficients was suggested first in Do and Vetterli (2003). It was shown that the optimum number of FRAT projections is $p + 1$, one projection for each column, and the best ordering of the 2D-FFT coefficients in these projections which is controlled by the normal vectors can be achieved if the normal vectors determined as:

$$\begin{aligned} (a_k, b_k) = \arg\min &\left\| \left(C_p(a_k), C_p(b_k) \right) \right\| \\ &(a_k, b_k) \in \{ nu_k : 1 \le n \le p-1 \} \\ &st.\ C_p(b_k) \ge 0 \end{aligned} \tag{6}$$

Here, $C_p(x)$ denotes the centralised function of period p; $C_p(x) = x - p.round(x/p)$.

Hence, $\left\| \left(C_p(a_k), C_p(b_k) \right) \right\|$ represents the distance from the origin to the point (a_k, b_k) on the Fourier plane. The constraint $C_p(b_k) \ge 0$ is imposed in order to remove the ambiguity in deciding between (a, b) and (–a, –b) as the normal vector for the projection. As a result, the optimal normal vectors are restricted to have angles in [0, π) and reordered matrix F is assigned symbol F_{opt}.

Finally, FRAT can be obtained by taking the 1D inverse fast Fourier transform (IFFT) for each column of the matrix F_{opt}. So, if the columns of the matrix F_{opt} are assigned, the symbol f_i, where i takes the values of 0, 1, 2, 3, … , p (Do and Vetterli, 2003), then:

$$r_i(k) = \operatorname{Re}\left\{ \frac{1}{p} \sum_{m=0}^{p-1} f(i) e^{j(2\pi/p)km} \right\} \tag{7}$$

Now, the matrix with the $r(i)$ columns represents the FRAT of A:

$$\Re = \left[r(1)\ r(2)\ r(3) \ldots r(p) \right] \tag{8}$$

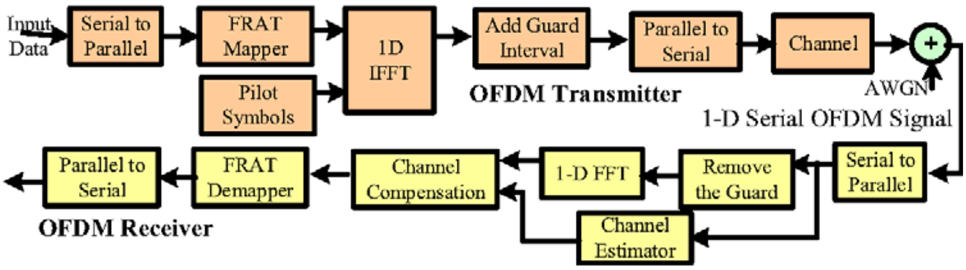
Also, Do and Vetterli (2003) showed that normalisation by the square root of the matrix size, p leads to better performance. Matrix A can be recovered by reversing the above procedure (taking 1D FFT, retrieving original Fourier coefficients ordering, and then taking 2D-IFFT).

3 The Radon-based OFDM mapping algorithm

Radon-based OFDM was proposed recently in Al-Jawhar et al. (2008), it was found that as a result of applying FRAT, the bit error rate (BER) performance was improved significantly, especially in the existence of multipath fading channels. Also, it is found that Radon-based OFDM structure is less sensitive to channel parameters variation, like maximum delay, path gain and maximum Doppler shift in selective fading channels as compared with standard OFDM structure (Kattoush et al., 2008).

In Radon-based OFDM system, FRAT mapping is used instead of quadrature amplitude modulation (QAM) mapping (Al-Jawhar et al., 2008) as shown in Figure 1. The other processing parts of the system remain the same as in conventional QAM OFDM system. It is known that FFT-based OFDM obtain the required orthogonality between subcarriers from the suitability of IFFT algorithm (Beylkin, 1987; Weinstein and Ebert, 1971; Lawrey, 1997; Wang and Giannakis, 2001; Lun et al., 2003a, 2003b). Using FRAT, mapping with the OFDM structure increases the orthogonality between subcarriers since FRAT computation uses 1D IFFT algorithm. Also, FRAT is designed to increase the spectral efficiency of the OFDM system through increasing the bit per Hertz of the mapping. Subcarriers are generated using N points discrete Fourier transform (DFT) and guard interval (GI) inserted at start of each symbol is used to reduce intersymbol interference (ISI).

Figure 1 Radon-based serial OFDM transceiver (see online version for colours)



The procedure steps of using the Radon-based OFDM mapping is as follows:

Step 1 Suppose $d(k)$ is the serial data stream to be transmitted using OFDM modulation scheme. Converting $d(k)$ from serial form to parallel form will construct a ID vector containing the data symbols to be transmitted,

$$d(k) = \left(d_0\, d_1\, d_2 \ldots\ldots d_n\right)^T \tag{9}$$

where k and n are the time index and the vector length respectively.

Step 2 Convert the data packet represented by the vector $d(k)$ from ID vector to a $p \times p$ 2D matrix $D(k)$, where p should be a prime number according to the matrix resize operation.

Step 3 Take the 2D FFT of the matrix $D(k)$ to obtain the matrix, $F(r, s)$. For simplicity, it will be labelled by F.

$$F(r,s)=\sum_{m=0}^{p-1}\sum_{n=0}^{p-1}D(m,n)e^{-j(2\pi/p)rm}e^{-j(2\pi/p)ns} \quad (10)$$

Step 4 Redistribute the elements of the matrix F according to the optimum ordering algorithm discussed earlier and given by equation (6). So, the dimensions of the resultant matrix will be $p \times (p + 1)$ and will be denoted by the symbol F_{opt}. For example, the two matrices for FRAT window = 7 are given by:

$$F=\begin{bmatrix} f_1 & f_8 & f_{15} & f_{22} & f_{29} & f_{36} & f_{43} \\ f_2 & f_9 & f_{16} & f_{23} & f_{30} & f_{37} & f_{44} \\ f_3 & f_{10} & f_{17} & f_{24} & f_{31} & f_{38} & f_{45} \\ f_4 & f_{11} & f_{18} & f_{25} & f_{32} & f_{39} & f_{46} \\ f_5 & f_{12} & f_{19} & f_{26} & f_{33} & f_{40} & f_{47} \\ f_6 & f_{13} & f_{20} & f_{27} & f_{34} & f_{41} & f_{48} \\ f_7 & f_{14} & f_{21} & f_{28} & f_{35} & f_{42} & f_{49} \end{bmatrix} \quad (11)$$

$$F_{opt}=\begin{bmatrix} f_1 & f_1 & f_1 & f_1 & f_1 & f_1 & f_1 & f_1 \\ f_2 & f_{10} & f_9 & f_{16} & f_8 & f_{21} & f_{14} & f_{13} \\ f_3 & f_{19} & f_{17} & f_{31} & f_{15} & f_{34} & f_{20} & f_{18} \\ f_4 & f_{28} & f_{25} & f_{46} & f_{22} & f_{47} & f_{26} & f_{23} \\ f_5 & f_{30} & f_{33} & f_{12} & f_{29} & f_{11} & f_{32} & f_{35} \\ f_6 & f_{39} & f_{41} & f_{27} & f_{36} & f_{24} & f_{38} & f_{40} \\ f_7 & f_{48} & f_{49} & f_{42} & f_{43} & f_{37} & f_{44} & f_{45} \end{bmatrix} \quad (12)$$

Step 5 Take the 1D-IFFT for each column of the matrix F_{opt} to obtain the matrix of Radon coefficients R:

$$R(k,n)=\frac{1}{p}\sum_{k=0}^{N-1}F_{opt}e^{\frac{j2\pi kn}{p}} \quad (13)$$

Step 6 Construct the complex matrix $\overline{R}$ from the real matrix R such that its dimensions will be $p \times (p + 1)/2$ according to:

$$\overline{r_{l,m}}=r_{i,j}+j\,r_{i,j+1},\; 0\le i\le p,\; 0\le j\le p \quad (14)$$

where $\overline{r_{l,m}}$ refers to the elements of the matrix $\overline{R}$, while $r_{i,j}$ refers to the elements of the matrix R. Matrices R and $\overline{R}$ are given by:

$$R = \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & \cdots\cdots & r_{1,p+1} \\ r_{2,1} & r_{2,2} & r_{2,3} & \cdots\cdots & r_{2,p+1} \\ \vdots & \vdots & \vdots & \cdots\cdots & \vdots \\ \vdots & \vdots & \vdots & \cdots\cdots & \vdots \\ r_{p-1,1} & r_{p-1,2} & \cdots\cdots & \cdots\cdots & r_{p-1,p+1} \\ r_{p,1} & r_{p,2} & r_{p,3} & \cdots\cdots & r_{p,p+1} \end{bmatrix} \quad (15)$$

$$\bar{R} = \begin{bmatrix} r_{1,1} + jr_{1,2} & r_{1,3} + jr_{1,4} & \cdots\cdots & r_{1,p} + jr_{1,p+1} \\ r_{2,1} + jr_{2,2} & r_{2,3} + jr_{2,4} & \cdots\cdots & r_{2,p} + jr_{2,p+1} \\ \vdots & \vdots & \cdots\cdots & \vdots \\ \vdots & \vdots & \cdots\cdots & \vdots \\ r_{p-1,1} + jr_{p-1,2} & \cdots\cdots & \cdots\cdots & r_{p-1,p} + jr_{p-1,p+1} \\ r_{p,1} + jr_{p,2} & \cdots\cdots & \cdots\cdots & r_{p,p} + jr_{p,p+1} \end{bmatrix} \quad (16)$$

Complex matrix construction is made for a purpose of increasing bit per Hertz of mapping before resizing mapped data.

Step 7 Resize the matrix $\bar{R}$ to a ID vector $r(k)$ of length $p \times (p + 1)/2$.

$$r(k) = \left(r_0\, r_1\, r_2 \ldots\ldots r_{p(p+1)/2}\right)^T \quad (17)$$

Step 8 Take the 1D-IFFT for the vector, $r(k)$ to obtain the subchannel modulation.

$$s(k) = \frac{1}{p(p+1)/2} \sum_{k=0}^{N_C-1} r(k)\, e^{\frac{j2\pi kn}{p(p+1)/2}} \quad (18)$$

where N_C is the number of carriers.

Step 9 Finally, convert the vector $s(k)$ to serial data symbols: $s_0, s_1, s_2, \ldots\ldots, s_n$.

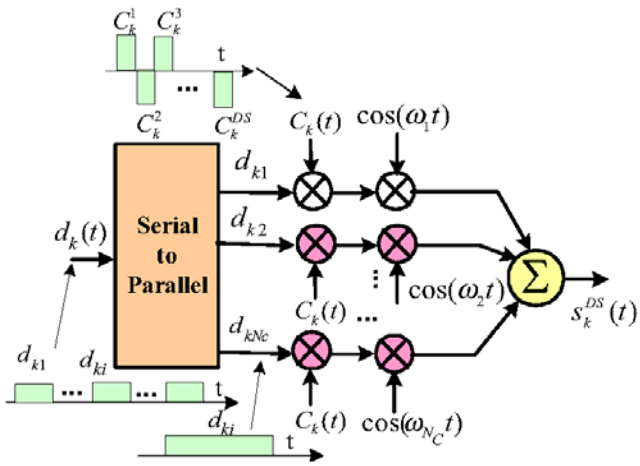
4 Radon-based MC-DS-CDMA system

MC-DS-CDMA system is a direct combination of DS-CDMA and the MC modulation. It is used for uplink cellular systems because the introduction of OFDM signalling into DS-CDMA scheme is effective for establishing a quasisynchronous channel (DaSilva and Sousa, 1993, 1994). The MC-DS-CDMA signal is generated by serial-to-parallel (S/P) converting the user data stream into N_C (the number of subcarriers) substreams, each of which is time spread and transmitted in an individual subcarrier.

In MC-DS-CDMA systems, the available channel bandwidth is divided into a set of equal width (possibly overlapped) subchannels and narrowband CDMA waveforms are transmitted over the subchannels.

Figure 2 shows the MC-DS-CDMA transmitter model for BPSK scheme (Hara and Prasad, 1997), where G_{DS} denotes the processing gain, N_C is the number of subcarriers and $c_k(t) = \left[c_k^1 \; c_k^2 \ldots c_k^{G_{DS}} \right]$ is the spreading code of the kth user. The power spectrum of the transmitted signal is the same as that of MC-CDMA.

Figure 2 MC-DS-CDMA transmitter system model (see online version for colours)



In the transmitter, the S/P converted data streams is spread using a given spreading code sequence in the time domain such that the resulting spectrum of each subcarrier can satisfy the orthogonality condition with minimum frequency separation. The transmitted signal is given by:

$$d_k^{DS}(t) = \sum_{i=1}^{N_C} d_{ki}(t) c_k(t) \cos(\omega_i t) \tag{19}$$

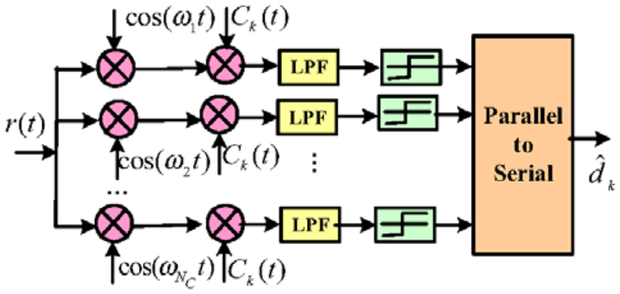
where $d_{ki}(t)$ is the kth user symbol waveform for carrier signal f_i. Since in each subchannel, the data is first spread with $c_k(t)$, then modulated with each subcarrier, the frequency difference between each adjacent carrier should be $\Delta f = \frac{G_{DS}}{N_C T_S}$ where T_S is the chip duration of spreading code. The total bandwidth required for transmitting such signal is $\left[G_{DS} \left(N_C + 1 \right) \right] / N_C T_S \Big]$.

Figure 3 shows the receiver of MC-DS-CDMA systems. It is composed of N_C single CDMA detector, the signal on each subcarrier is required to be frequency non-selective fading, that is, the channel should have a constant gain and linear phase response over a bandwidth that is greater than the bandwidth of the signal (DaSilva and Sousa, 1993). The received signal $r(t)$ for all K users is given by:

$$r(t) = \sum_{k=1}^{K} \sum_{i=1}^{N_C} d_{ki}(t) \, c_k(t) \, h(i) \cos(\omega_i t) + n(t) \tag{20}$$

where $n(t)$ is the additive white Gaussian noise (AWGN) and $h(i)$ is the complex signal channel coefficient of the ith subcarrier.

Figure 3 MC-DS-CDMA receiver system model (see online version for colours)



This signal is first mixed with each subcarrier to get the baseband signals, which is then despread by multiplying the signal with a locally generated pseudo-noise (PN) sequence and then detected. Note that the received signal does not account for the multipath and fading effects.

This scheme without forward error correction (FEC) among subcarriers cannot achieve any frequency diversity. A modified scheme was proposed in Kondo and Milstein (1996) to achieve narrowband interference suppression, in which the same spread sequence modulates several subcarriers, which allow exploiting frequency diversity. Another version of MC-DS-CDMA scheme has been suggested in Sourour and Nakagawa (1996), which transmits the same data using several subcarriers (achieve frequency domain diversity).

In the proposed design, the FFT-based OFDM is replaced by the Radon-based OFDM described in Section 3 which has a better performance and a reduced ISI and ICI with comparison with FFT-based OFDM (Al-Jawhar et al., 2008).

Suppose d is a stream of serial data to be transmitted using Radon-based MC-DS-CDMA. The procedure steps of using the Radon-based OFDM in the realisation of the Radon-based MC-DS-CDMA transceiver are as follows:

Step 1 Convert the data streams from S/P form to construct a 1D vector containing the data symbols to be transmitted,

$$d = \left(d_0\, d_1\, d_2 \ldots\ldots\ldots d_{L-1}\right)^T \tag{21}$$

where L is the packet length and also refers to the code length.

Step 2 Each S/P converted data symbol is direct sequence spectrum spread (DS-SS) modulated using a user specific spreading code. As a result, each data symbol becomes a vector with L bits and as a result a matrix D of size L by L is obtained.

Step 3 Each raw in the matrix D, which represents the spreaded data symbol, is transmitted over one of the N_C subcarriers using the Radon-based OFDM.

Step 4 Finally, the resultant signals in each subchannel are parallel-to-serial converted and the output signal is given by equation (1):

$$s^{(k)}(t) = \sum_{n=0}^{N_C-1} d_n^{(k)} c^{(k)}(t) e^{j2\pi f_n t}, \qquad 0 \le t \le N_C T_d \tag{22}$$

where T_d is the bit duration and $c^{(k)}$ is the kth user spreading code respectively.

Figure 4 The schematic diagram of the proposed MC-DS-CDMA transmitter steps realisation (see online version for colours)

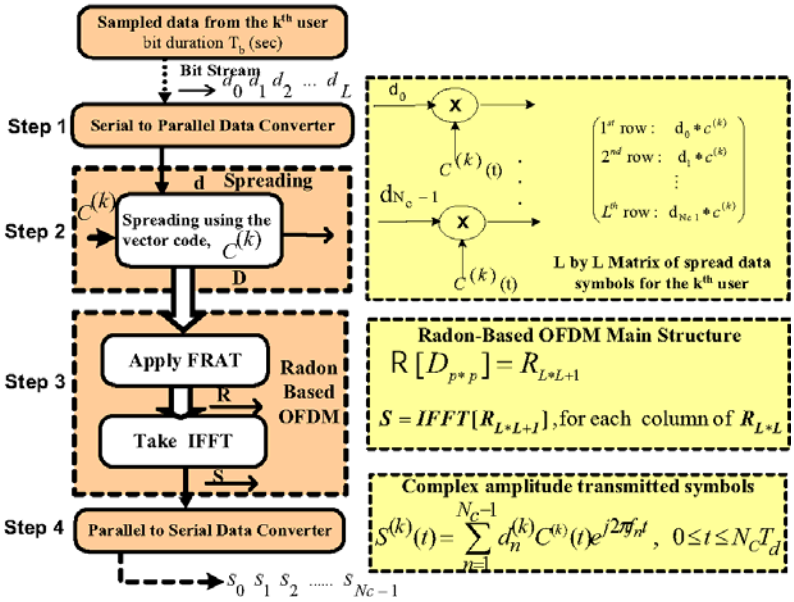


Figure 5 The schematic diagram of the proposed MC-DS-CDMA receiver steps realisation (see online version for colours)

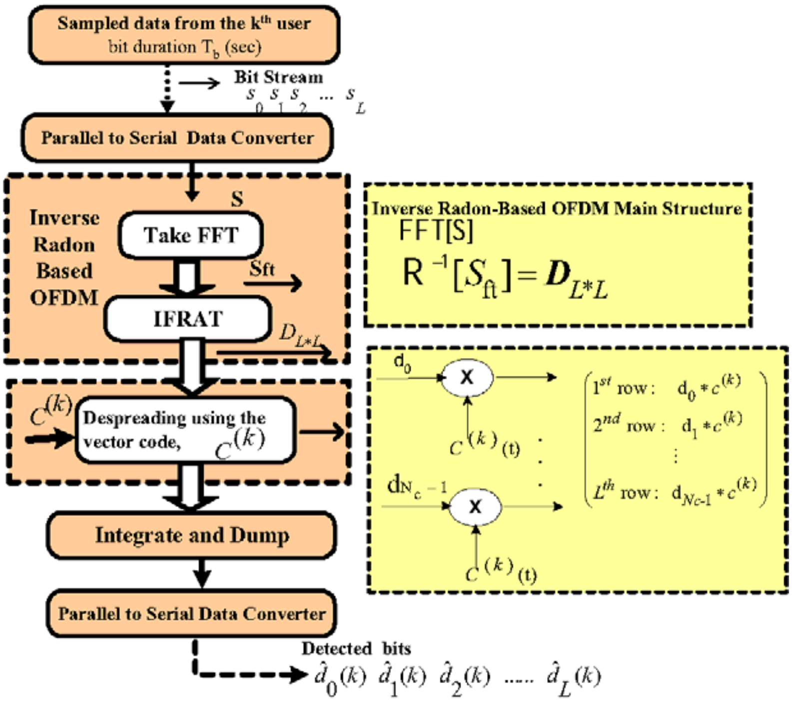
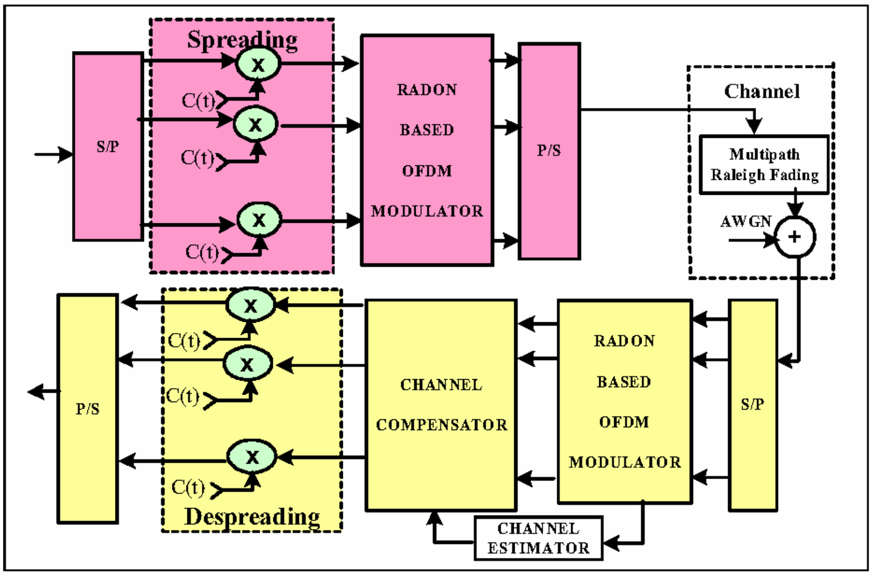


Figure 4 depicts in details the realisation of the above steps in the proposed procedure for realisation of the Radon-based MC-DS-CDMA transmitter, while Figure 5 depicts the schematic diagram of the proposed procedure for realisation of the Radon-based MC-DS-CDMA receiver of the upper transmitter.

5 Performance analysis of the proposed MC-DS-CDMA

In this section, the results of bit error performance simulations for Radon-based MC-DS-CDMA are provided and compared with the conventional MC-DS-CDMA under different channel conditions. AWGN channels, flat fading channels and selective fading channels are considered during simulations. A PN code of length $L = 7$ is implemented in the simulations. The schematic diagram of the proposed MC-DS-CDMA transceiver used in simulations is provided in Figure 6.

Figure 6 Proposed MC-DS-CDMA transceiver structure (see online version for colours)

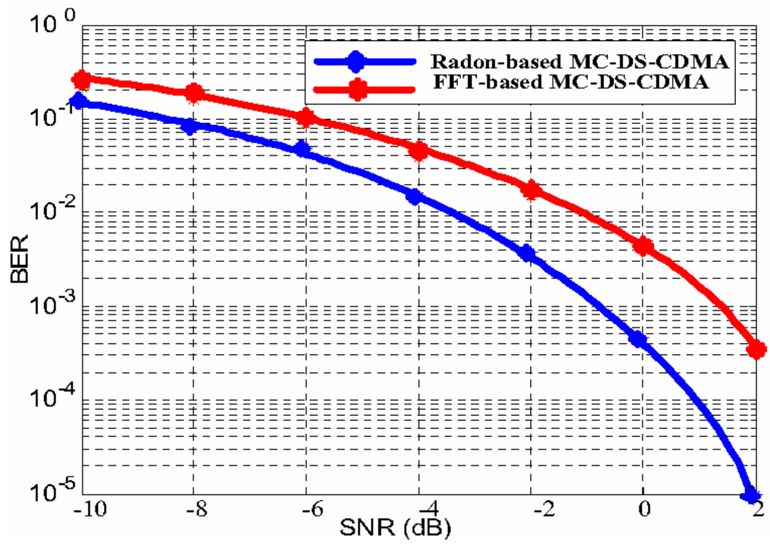


The time domain envelope and the power spectrum of the proposed Radon-based MC-DS-CDMA was simulated and tested in a multipath frequency selective Rayleigh distributed channels with AWGN. Two ray channels were assumed in simulations with a second path delay of –8 dB, a maximum delay for the second path of $\tau_{max} = 1$ µsec and a maximum Doppler shift $f_{Dmax} = 4$ Hz for several values of signal-to-noise ratio (SNR).

The same simulations were repeated for a symbol time duration $T_d = 2$ µsec, a maximum delay in the second path $\tau_{max} = 10$ µsec and $f_{Dmax} = 1{,}000$ Hz. The obtained results were as good as those of conventional MC-DS-CDMA under the same conditions.

The BER performances of the proposed Radon-based MC-DS-CDMA and conventional MC-DS-CDMA systems in AWGN channel are shown in Figure 7. From which it can be noted that Radon-based MC-DS-CDMA has an SNR gain of 2 dB compared with conventional system to achieve BER of 10^{-3}.

Figure 7 Performance of Radon-based MC-DS-CDMA for AWGN channel (see online version for colours)



The simulation of proposed system in a flat Raleigh-distributed fading channel with AWGN is given in Figure 8. It shows that the Radon-based MC-DS-CDMA has a gain in SNR of more than 3.8 dB as compared with the conventional MC-DS-CDMA to achieve a BER performance of 10^{-3}.

Figure 8 Performance of Radon-based MC-DS-CDMA in flat fading channel (see online version for colours)

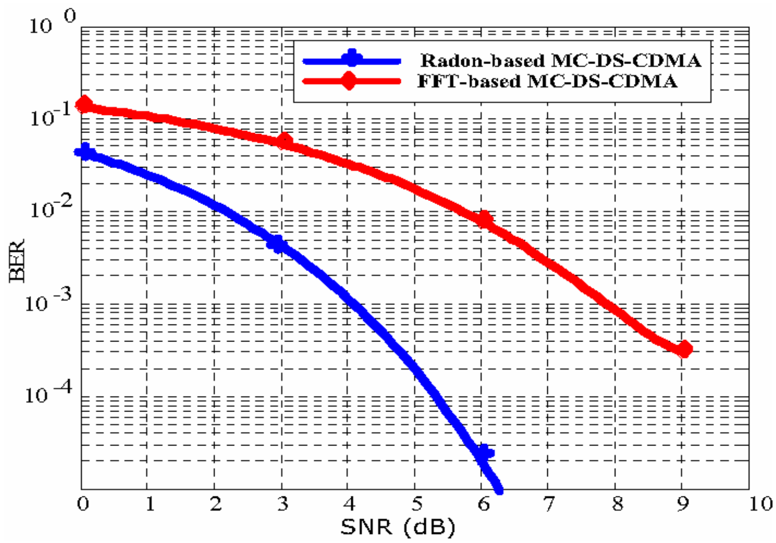
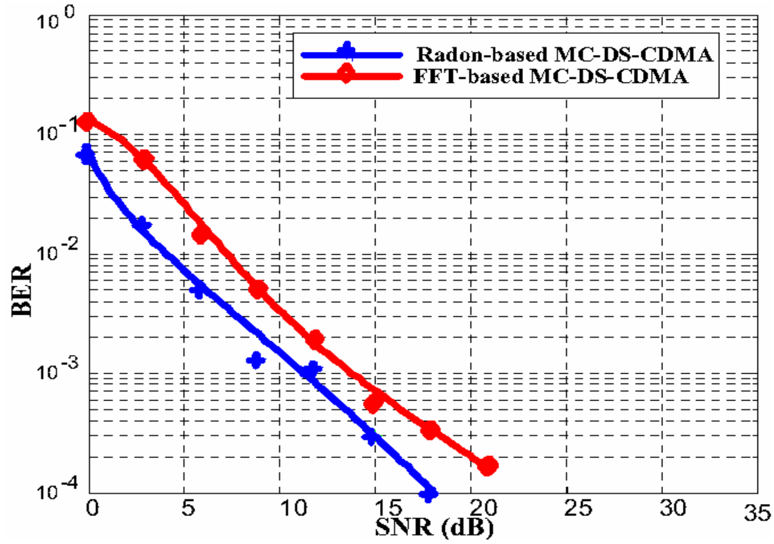


Figure 9 shows the BER performance of Radon-based MC-DS-CDMA in a two-ray Rayleigh-distributed multipath fading channel were the second path gain and delay was –8 dB and τ_{max} = 1 µsec respectively. It can be seen that BER performance of the

Radon-based MC-DS-CDMA has an advantage of about 4 dB in SNR as compared with the conventional MC-DS-CDMA, and as in the case of flat fading channel, it is still better than the conventional MC-DS-CDMA. It requires 18 dB of SNR for proposed MC-DS-CDMA to reach BER of 10^{-4}, while the conventional MC-DS-CDMA does not achieve such a BER without more complex equalisation.

Figure 9 Performance of the proposed MC-DS-CDMA in frequency selective fading channel (see online version for colours)



6 Effect of channel parameters variations on the proposed system performance

The effect of variations of selective fading channel parameters on the performance of the proposed system is simulated and studied. The effect of changing the second path gain on the BER performance of both proposed and conventional MC-DS-CDMA is simulated and provided in Figure 10. Two cases are studied, second path gain = –8 dB and second path gain = –12 dB at $f_{D\max}$ = 4 Hz and the second path delay is kept at 1 µsec ($\tau_{\max}$ = 1 µsec). From the simulations, it is seen that the effect of the second path gain on the performance of proposed system is less divesting than that of conventional system and proposed system has an advantage of about 4 dB SNR compared with conventional to have BER = 10^{-3}. It requires 6.5 dB of SNR for proposed MC-DS-CDMA to reach BER of 10^{-4}, while the conventional MC-DS-CDMA does not achieve such a BER without more complex equalisation.

Figure 11 shows the effect of the second path delay ($\tau_{\max}$) on the BER performance of the two systems when the second path gain of –12 dB. Two cases are studied, $\tau_{\max}$ = 0.1 µsec and $\tau_{\max}$ = 2 µsec. Again, it is seen that the second path delay has less effect on proposed system compared with conventional system and the proposed system has an advantage of about 4 dB in SNR.

Figure 10 Effect of the second path gain on the BER performance for the proposed MC-DS-CDMA (see online version for colours)

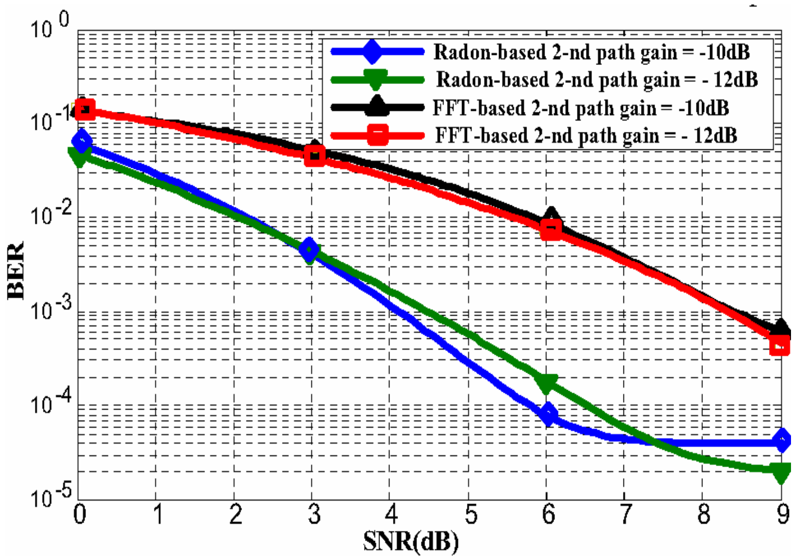


Figure 11 Effect of the second path delay on the BER performance for the proposed MC-DS-CDMA (see online version for colours)

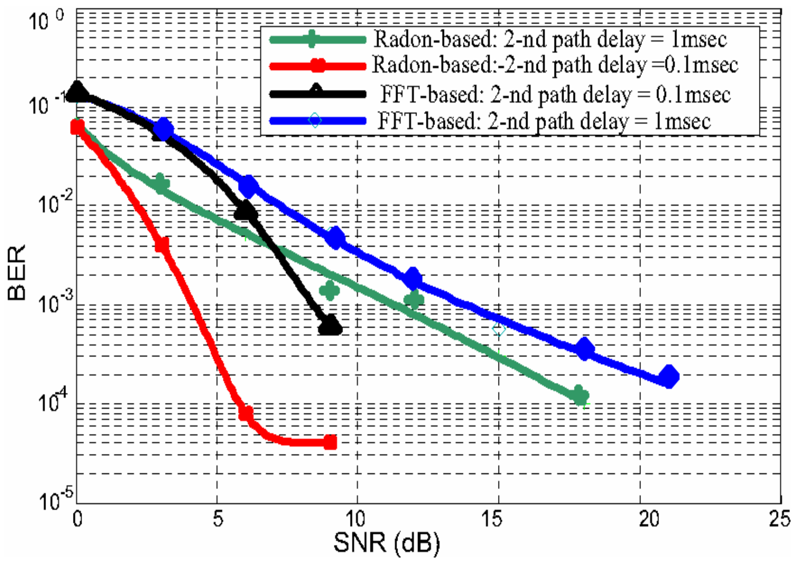
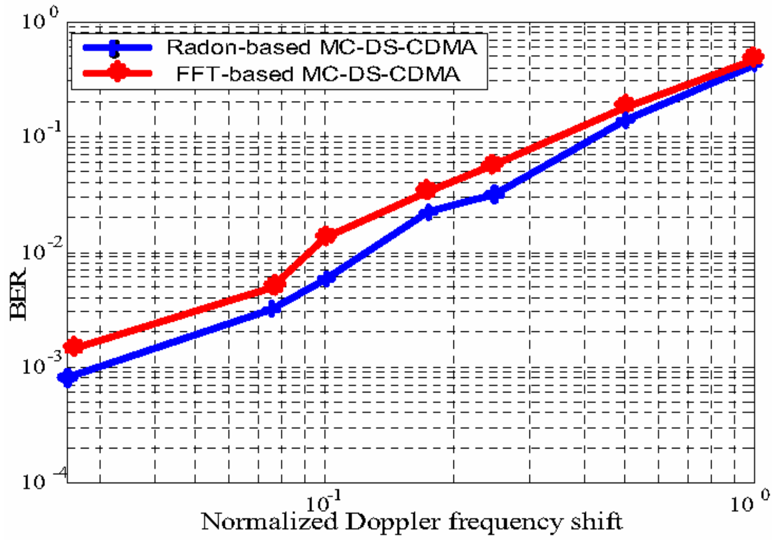


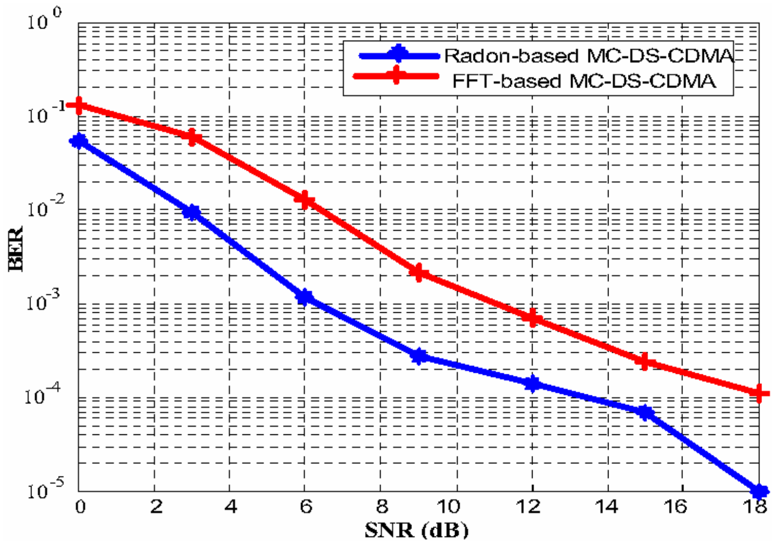
Figure 12 shows the effect of the normalised Doppler frequency shift on the BER when SNR = 15 dB, $f_{D\max}$ = 4,000 Hz, the second path gain = –8 dB and $\tau_{\max}$ = 1 µsec respectively. It is seen from Figure 12 that even with small $f_{D\max}$, the conventional system error is higher than that of the proposed Radon-based MC-DS-CDMA.

Figure 12 The effect of normalised Doppler shift on the BER for the proposed MC-DS-CDMA (see online version for colours)



The BER performance of both proposed and conventional systems was tested in a real multipath fading channel, the COST207 in rural area environment with six taps. The results provided in Figure 13 shows that the proposed systems is still better than the conventional one and an SNR gain of 5 dB is achieved by proposed Radon-based MC-DS-CDMA to have BER equal 10^{-4}.

Figure 13 Proposed MC-DS-CDMA BER in rural area for COST207 multipath fading (see online version for colours)



7 Conclusions

In this paper, a novel MC-DS-CDMA system is designed and simulated. An FRAT is used in a Radon-based-OFDM transceiver scheme used in proposed MC-DS-CDMA system. The FRAT is used as a data mapper instead of the conventional PSK and QAM techniques. The proposed Radon-based MC-DS-CDMA has a better performance than conventional especially under multipath frequency selective fading conditions. The results shows an SNR gain of 1 dB, 4.5 dB and 8 dB in AWGN, flat fading and frequency selective channels, respectively, under the same conditions of the channel parameters. Radon-based MC-DS-CDMA is less sensitive to channel parameters variations, like maximum delay, path gain and maximum Doppler shift in selective fading channels as compared with the standard structure. The use of FRAT in MC-DS-CDMA maintains a spectrum shape and efficiency as good as the standard MC-DS-CDMA. A spectral efficiency of about 1.75 is achieved using Radon-based structures with an FRAT window of 7 × 7 due to the use of the complex data constellation. This efficiency can be increased up to approximately two if the FRAT window is increased, which represents the case of quadrature phase shift keying mapping.

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