Performance Evaluation of STBC-OFDM WiMAX System using Graphics Processing Unit (GPU)

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***Abstract*—In recent years, graphics processing unit (GPU) has escalated interest in computational applications. In this paper, we proposed an efficient implementation of multiple-input multiple-output orthogonal frequency division multiplexing (MIMO-OFDM) worldwide interoperability for microwave access (WiMAX) communication system using GPU. The WiMAX system uses space time block code (STBC) and maximal ratio receive combining (MRRC), which is computationally rich due to complex multiplication and fast fourier transform (FFT) computation. To harness the benefits of GPU computing power the complex multiplications in MRRC and FFT are computed in parallel. The processing time for FFT and MRRC under CPU and GPU environment are analyzed and presented.**

Keywords: GPU, WiMAX, OFDM, STBC, MRRC, Equalization, Rayleigh fading channel

I. Introduction

The worldwide interoperability for microwave access (WiMAX) is developed for wireless broadband in the line of sight based point to multi-point communication [1]. The original 802.16 standard (2001) is based on the single-carrier physical (PHY) layer with a burst time division multiplexed (TDM) MAC layer. Subsequently it included non-line of sight applications in the frequency range of 2GHz-11GHz, with the addition of a physical layer based on OFDM along with orthogonal frequency division multiple access (OFDMA) in MAC layer. This resulted in a new standard known as IEEE 802.16-2004 fixed wireless communication standard. In 2005 WiMAX group came up with IEEE 802.16-2005 standard, the mobile WiMAX system [2, 3]. The WiMAX is seen to be very demanding standard, to meet the high data rate services with high spectral efficiency. This technology is designed to provide a peak data rate of 75 Mbps in downlink and 25 Mbps in uplink operating in 20 MHz bandwidth [3, 4]. To support such a high data rate application, the system employs OFDM with MIMO technologies. OFDM technology requires computation of IFFT and FFT at the transmitter and the receiver respectively [5].

STBC is a special form of MIMO, proposed by Alamouti in 1998 and originally employed 2 transmit and 1 receive antenna in flat fading channel [6]. IEEE 802.16e supports 1×2, 1×4 antenna system in uplink and 2×2 in downlink. In uplink scenario, for 1×2 and 1×4 antenna system, MRRC is used to combine the data at receiver, while in downlink zero-forcing equalization is performed to nullify the channel effect. Implementing these along with baseband processing is quit challenging. Here equalization, IFFT, FFT and combining at the receiver constitutes major computationally challenge and contribute to power usage portion of system design. Thus, any performance gain in these blocks can potentially improve the throughput of the whole system significantly.

GPU based computing is a recent paradigm in computational research [7, 8]. GPU is a low cost programmable array of streaming processors, which can achieve high throughput by computing large blocks of data in parallel. It has evolved as general purpose GPU (GPGPU) processing technology allowing users to process large blocks of parallel data using an array of low complexity processors employing a large number of streaming processors to execute a common set of data operations in parallel. In this paper implementation of MRRC scheme and FFT computation under GPU environment presented.

Following this introduction, the remaining paper is organized as under. Section II discusses the WiMAX down-link communication system and mathematical model for STBC scheme, MRRC scheme and zero-forcing equalization for 2×2 STBC-OFDM system. Section III provides introduction of GPU architecture. Section IV represents physical layer overview of IEEE 802.16e, WiMAX up-link system and computational complexity issues. Section V presents the simulation framework along with a discussion on the result and finally section VI provides the concluding remarks.

II. IEEE 802.16e WiMAX: The mathematical model

The mathematical model of the mobile communication schemes used in WiMAX in this paper is presented below:

A. WiMAX System Downlink Communication System

The IEEE 802.16e supports two transmit antenna and two receive antenna i.e a 2×2 system. Fig. 1 presents (2×2) STBC-OFDM system. The data is modulated and then passed through the STBC encoder where data is separated in two sequences presented as X_1 and X_2 [9, 10]. After serial to parallel (S/P) conversion, N-point IFFT is performed on separate data sequences, which converts the data from frequency domain to time domain and signal is back converted from parallel to serial (P/S), after addition of cyclic prefix (CP) and up-converted data is transmitted through different antennas followed by the STBC encoding scheme as presented in Table I and Table II.

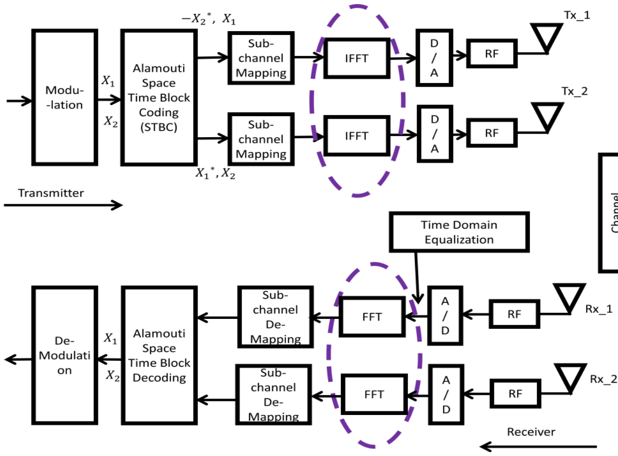

Fig. 1. STBC-OFDM (2×2) system

The transmitted signal is passed through rayleigh flat fading channel. At the receiving end after the down-conversion CP is removed and time domain equalization is implemented (assuming known channel coefficients). At the receiving end after S/P conversion to get data in frequency domain N-point FFT is performed on each signal separately. Followed by STBC decoding, demodulation is done to obtain the transmitted data at the receiver.

B. STBC Scheme for 2×2 antenna system

According to STBC scheme in first time interval, signal X_1 is transmitted from antenna 1 and signal X_2 is transmitted from antenna 2. In the second time interval signal $-X_2^*$ is transmitted from antenna 1 and signal X_1^* is transmitted from antenna 2 [6]. This encoding scheme is presented in Table I Since, the two signal is transmitted in two symbol periods, the coding rate of STBC is one. As STBC codes are orthogonal to each other, the signal can be recovered at the receiver using simple linear combining scheme.

TABLE I
ALAMOUTI'S STBC ENCODING SCHEME

Space→ / Time↓

	T_X antenna 1	T_X antenna 2
Time t	X_1	X_2
Time t+T	-X_2*	X_1*

TABLE II
THE CHANNEL COEFFICIENTS BETWEEN TRANSMIT AND RECEIVE ANTENNAS

	R_X antenna 1	R_X antenna 2
T_X antenna 1	h_{11}	h_{12}
T_X antenna 2	h_{21}	h_{22}

The received signal at 1^{st} time slot and 2^{nd} time slot can be represented as

$$r_1 = \begin{bmatrix} h_{11} & h_{21} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + n_1 \quad (1)$$

$$r_2 = \begin{bmatrix} h_{11} & h_{21} \end{bmatrix} \begin{bmatrix} -X_2^* \\ X_1^* \end{bmatrix} + n_2 \quad (2)$$

$$r_3 = \begin{bmatrix} h_{12} & h_{22} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + n_3 \quad (3)$$

$$r_4 = \begin{bmatrix} h_{12} & h_{22} \end{bmatrix} \begin{bmatrix} -X_2^* \\ X_1^* \end{bmatrix} + n_4 \quad (4)$$

Where, n_1, n_2, n_3, n_4 are additive white gaussian noise (AWGN) and h_{11}, h_{12}, h_{21} and h_{22} are flat fading channel coefficients.

C. Maximal Ratio Receive Combining (MRRC) Scheme

MRRC is a form of space diversity. Fig. 2 presents a two-branch (1×2) MRRC scheme. The MRRC scheme states that the signal X_1 is transmitted from antenna, this signal passes through the two different channels with coefficients h_1 and h_2 with noise coefficients n_1 and n_2 respectively [6]. The received base band signal r_1 and r_2 at receiving antenna R_X_1 and R_X_2 can be represented as

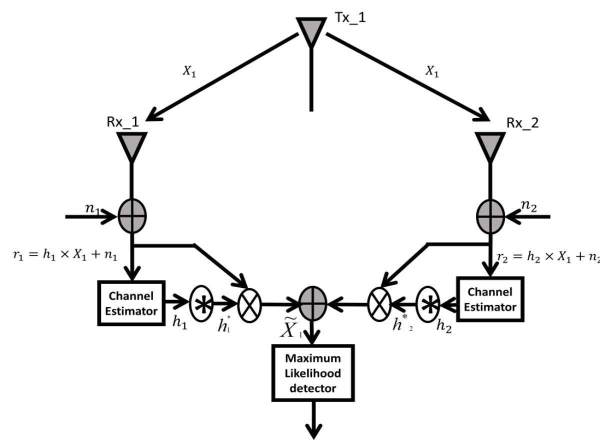

Fig. 2. Two-branch (1×2) MRRC-scheme

$$r_1 = h_1\, X_1 + n_1 \quad (5)$$

$$r_2 = h_2\, X_1 + n_2 \quad (6)$$

The received combining scheme for 1×2 antenna system is given by

$$\tilde{X}_1 = h_1^*\, r_1 + h_2^*\, r_2 \quad (7)$$

where, $\tilde{X}_1$ is the expected received signal for the transmitted signal X_1. Similarly the MRRC can be represented for 1 transmitting antenna and 4 receiving antenna (1×4) . It may be noted that the channel coefficient h_i for $i = 1, 2, 3, 4$ is under flat fading environment. Hence rayleigh fading relationship for four-branch MRRC scheme can be represented as

$$\tilde{X}_1 = h^*{}_1\, r_1 + h^*{}_2\, r_2 + h^*{}_3\, r_3 + h^*{}_4\, r_4 \quad (8)$$

where, h_i is the i^{th} flat fading channel coefficient for $i = 1, 2, 3, 4$ and r_j is base-band received signal at j^{th} antenna for $j = 1, 2, 3, 4$.

D. Zero-Forcing (ZF) Equalization

Signal detection can be achieved by simple ZF equalization. The ZF equalizer removes all inter symbol interference (ISI) and applies channel inversion and can eliminate multiple access interference (MAI) by restoring the orthogonality with an equalization coefficient. The ZF equalizer results in noise amplification but it is simple to implement.
The signal vector at the receiver from (5) and (6) is given by

$$\begin{bmatrix} r_1 \\ r_2^* \\ r_3 \\ r_4^* \end{bmatrix} = \begin{bmatrix} h_{11} & h_{21} \\ h_{21}^* & -h_{11}^* \\ h_{12} & h_{22} \\ h_{22}^* & -h_{12}^* \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2{}^* \\ n_3 \\ n_4{}^* \end{bmatrix} \tag{9}$$

To detect the X_1 and X_2 the ZF equalization is implemented as under
Let

$$H = \begin{bmatrix} h_{11} & h_{21} \\ h_{21}^* & -h_{11}^* \\ h_{12} & h_{22} \\ h_{22}^* & -h_{12}^* \end{bmatrix}, \quad and \quad \bar{R} = \begin{bmatrix} r_1 \\ r_2^* \\ r_3 \\ r_4^* \end{bmatrix} \tag{10}$$

Here, H is a modified channel matrix. Hence, pseudo inverse of channel matrix is given by

$$W = \left(H^H H\right)^{-1} H^H \tag{11}$$

Thus transmitted signal can be estimated using

$$\hat{X} = \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = W\bar{R} = \left(H^H H\right)^{-1} H^H \times \bar{R} \tag{12}$$

Here, $\hat{X}$ is the estimated signal, originally transmitted from transmitting antennas. The standard MRRC for MIMO-OFDM communication system is implemented on GPU hardware. Next section provides an introduction to GPU.

III. GPU Architecture: An Introduction

The block diagram of a GPU system is presented in Fig. 3. A GPU consists of multiple processors and an array of smaller streaming multi-processors (SM) with their shared memory and individual cache memory. Currently, a single GPU can have thousands of compute unified device architecture (CUDA) streaming processors (SP). For example K40 has 2880 CUDA streaming processors. These systems have the capability of high processing throughput through parallelization. CUDA is a parallel computing platform and programming model created by NVIDIA and implemented on the GPUs. It enables increase in computing capability and harnessing the power of GPU [7, 8, 11].

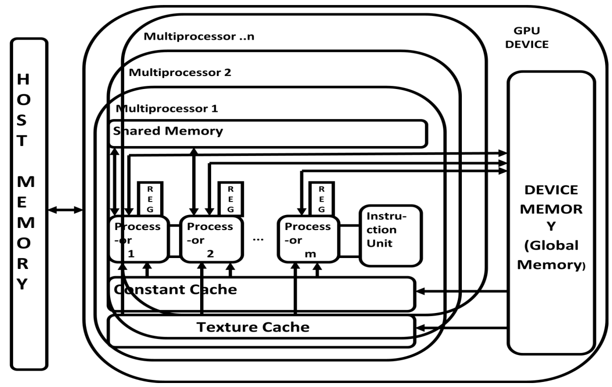

Fig. 3. NVIDIA GPU device architecture

IV. WiMAX System Overview

This section provides the basic overview of the WiMAX uplink and downlink system, The mobile WiMAX profile is based on the principles of OFDM by adopting a scalable OFDMA-based PHY (physical) layer. Table III shows WiMAX parameters and bandwidth-scaling process for a 5 ms frame duration, where the cyclic prefix (CP) duration is $1/8$ of the useful symbol duration [4, 9]. The scalability of the system bandwidth depends on the FFT size, while the sub-carrier frequency spacing remains fixed at 10.94 KHz. Hence the OFDMA symbol duration is also fixed. In both downlink and uplink, sub-carriers are grouped into subsets of sub-carriers called sub-channels. The Fig. 4 represents the basic frame structure of WiMAX system. One frame consists eight sub-frame and each sub-frame contains six OFDM symbols [12].

TABLE III
IEEE 802.16e OFDMA parameters [4]

System bandwidth (MHz)	1.25	2.5	5	10	20
Sampling frequency (MHz)	1.8	2.8	5.6	11.2	22.4
FFT size	128	256	512	1024	2048
Sub-carrier spacing (KHz)	10.94				
OFDM symbol duration (μs)	102.86				
Useful symbol time (μs)	91.43				
Cyclic perfix (μs)	11.43				

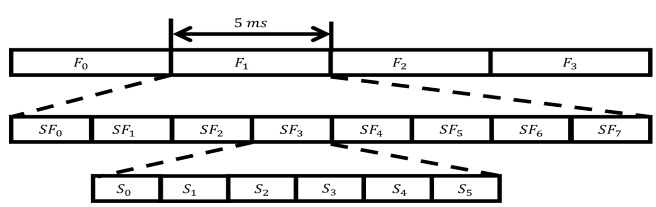

Fig. 4. IEEE 802.16e basic frame structure

A. WiMAX System Uplink: Implementation using GPU

The IEEE 802.16e system uses the same OFDMA-PHY layer specification in uplink and downlink as presented in Table III. The system uses $(1\ T_X \times N\ R_X)$ antenna configuration in uplink with 1×2 antenna system as baseline. This paper consider the performance analysis of 1×2 and 1×4 antenna MRRC-OFDM system under GPU environment. The simple MRRC scheme is presented in Fig. 2. The general procedure to compute 1×2 MRRC scheme under GPU environment is presented in Fig. 5 and it can be easily extend for 1×4 MRRC scheme.

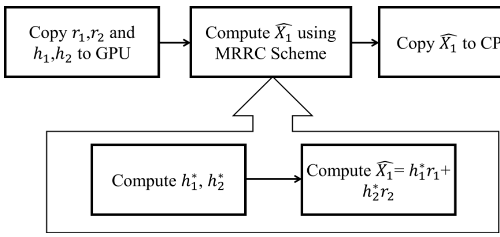

Fig. 5. General procedure for computation of 1×2 MRRC scheme under GPU environment

B. Computational Complexity Issues

From the block diagram in the Fig. 2 and Fig. 1 it can be observed that fundamental blocks of an OFDM system comprise of cyclic prefix addition and removal, FFT, IFFT operation and MRRC combining. Out of these FFT and IFFT operations, equalization, MRRC combining consume substantial processing resources when large quantity of data has to be processed. The frame structure presented in Fig. 4 has 48 OFDM symbols in one frame with 2048 point FFT for 20 MHz WiMAX system specification and has peak data rate of 75 Mbps in downlink and 25 Mbps in uplink. The FFT and MRRC combining operations consume majority of the computational resource in a sequential processing environment. The operation of FFT, MRRC can be compute in parallel, since GPU provide a performance speedup using parallel implementation [13–15]. Hence performance of these operations under GPU environment is proposed in this paper.

V. Simulation Results and Discussion

The simulation for downlink and uplink WiMAX system under central processing unit (CPU) or host and GPU or device environment is presented in this section. The performance of WiMAX transceiver is evaluated through simulation. The simulations were done using MATLAB software. The system hardware consists of a host PC with Intel Xeon, $E5-2650$ processor operating at 2.0 GHz clock frequency with Linux operating system. NVIDIA Tesla $M-2090$ graphics card with 512 streaming processors at 1.3 GHz clock frequency is used. Parallel computing toolbox in MATLAB is used for simulation in the GPU environment.

Here, MIMO-OFDM simulation is carried out using WiMAX parameter specification in frequency division duplexing (FDD) mode of operation as given in table III for both uplink and downlink. One frame is transmitted by one user hence, OFDMA is not addressed in this paper the whole simulations is performed for single user.

A. WiMAX System downlink performance

In downlink system the simulation is carried out using 2×2 MIMO-OFDM system as shown in Fig. 1. The user data is converted to symbols using any one of the modulation scheme- BPSK, QPSK, 16-QAM and 64-QAM. The major simulation parameter is considered as presented in Table IV. The FFT

TABLE IV
Major simulation parameters for BER calculation

Parameters	Downlink	Uplink
System Bandwidth (MHz)	20 MHz	20 MHz
FFT Size	2048	2048
Cyclic Prefix	1 / 8 of OFDM symbol duration	1 / 8 of OFDM symbol duration
Total OFDM Symbols / Frame	48	48
Modulation	BPSK / QPSK / 16-QAM / 64 QAM	BPSK / QPSK / 16-QAM / 64 QAM
Tx / Rx Antennas	2×2	1×2, 1×4
Channel	Rayleigh (single Tap)	Rayleigh (single Tap)
Equalization	Zero-Forcing	-
Combining Scheme	Linear Combining	Maximal Ratio Receive Combining (MRRC)

computation is processed under GPU environment for 2×2 MIMO-OFDM system and the speed-up obtained for different channel bandwidths based on different number of FFT points for one transmit WiMAX frame of 5ms is presented in Fig. 6. From Fig. 6 it is observed that the speedup for FFT processing

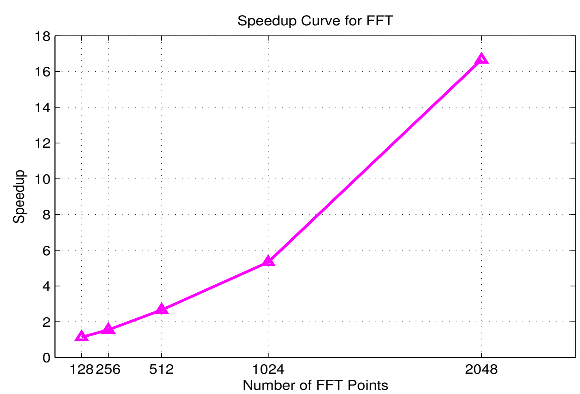

Fig. 6. FFT speedup curve for 2×2 STBC-OFDM system

is highest (16.73) for 20 MHz channel bandwidth with 2048 point FFT while, in case of 1.25 MHz channel bandwidth with 128 FFT points it is lowest (1.23). Hence the performance of GPU improves as the amount of data to be processed is increases.

The comparison between bit error rate (BER) and signal to noise ratio (SNR) using above discussed modulation schemes is carried out in host and GPU environment using monte-carlo simulation in rayleigh flat fading (single tap) channel and presented in Fig. 7.

The complete analysis of the time taken to process different point FFT by CPU and GPU is presented in Table V. Hence, processing of large data at the base station can made faster by using GPU accelerator at the cost of time taken to transfer the data from CPU to GPU, discussed in later case.

TABLE V
PERFORMANCE COMPARISON OF CPU AND GPU

No. of FFT Points	Time in (ms)		**Speedup**	System Bandwidth in (MHz)	MRRC-OFDM (1 X 2) time in (ms)			**Speedup**	MRRC-OFDM (1 X 4) time in (ms)			**Speedup**
	CPU	GPU			CPU	Data transfer time (CPU to GPU)	GPU		CPU	Data transfer time (CPU to GPU)	GPU	
128	0.600	0.487	1.23	1.25	3.3	0.8	2.5	0.99	6.1	1.10	4.0	1.20
256	0.800	0.496	1.61	2.5	5.50	1.20	2.4	1.56	14.8	2.5	4.7	2.06
512	1.400	0.509	2.75	5	12.80	1.90	3.1	2.58	27.4	4.6	4.8	2.90
1024	2.700	0.513	5.26	10	29	4.9	4.2	3.18	58.8	9.5	6.1	3.75
2048	8.900	0.532	16.73	20	54.2	7	4.8	4.58	113.5	10.6	6.5	6.65

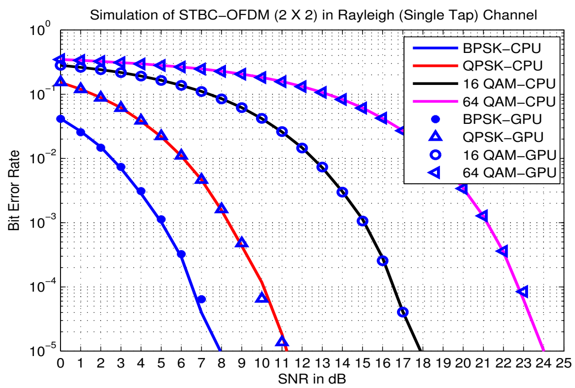

Fig. 7. BER vs SNR curve for 2×2 STBC-OFDM WiMAX downlink system in Rayleigh flat fading channel

B. WiMAX System uplink performance

Simulation of WiMAX uplink system for 1×2 is presented in Fig. 8. It shows BER vs SNR for (1×2) MRRC-OFDM under CPU and GPU environment. Performance of the system for different modulation schemes supported by WiMAX system under CPU and GPU environment is evaluated, it can be observed that BER performance is equal in both CPU & GPU environment. The main motive behind using the GPU computing system is to reduce the computational time when large data has to be processed. MRRC-OFDM system has better performance of approximately 5 dB at BER of 10^{-3} in comparison to simple two branch MRRC scheme for BPSK modulation.

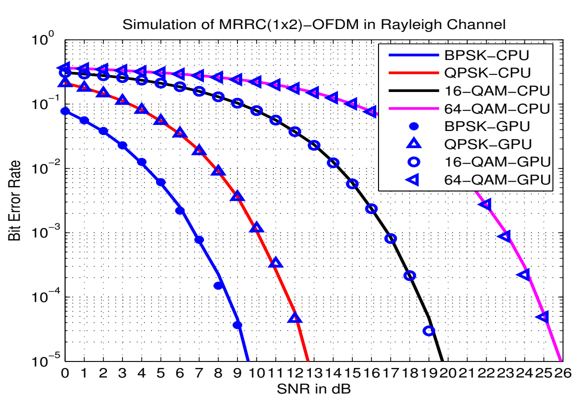

Fig. 8. BER vs SNR curve for 1×2 MRRC-OFDM WiMAX uplink system in Rayleigh flat fading channel

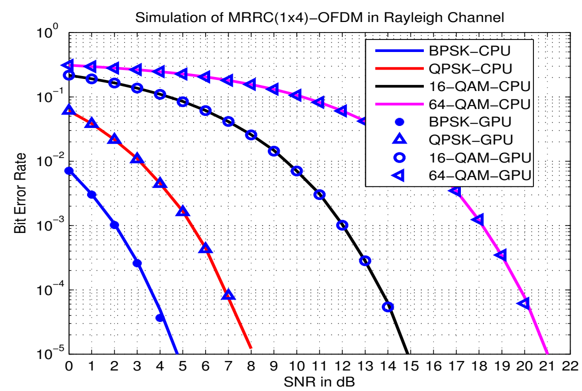

Fig. 9. BER vs SNR curve for 1×4 MRRC-OFDM WiMAX uplink system in Rayleigh flat fading channel

Fig. 9 presents simulation of 1×4 MRRC-OFDM system under CPU and GPU environment, has 5dB better performance at BER of 10^{-3} in comparison to the simple 1×4 MRRC scheme.

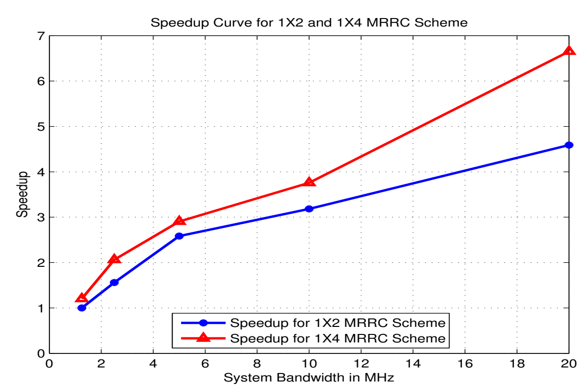

Fig. 10. Speedup comparison for 1×2 and 1×4 MRRC system

From the Fig. 10 it is observed that the speedup for 1×4 MRRC-OFDM WiMAX system is greater than 1×2 MRRC-OFDM WiMAX (given in Table V) due to the large quantity of data combining and parallel complex multiplications at the receiving end. The time to move data from CPU to GPU also increases along with complexity of the system. From Table V it can be observed that, even the time needed to move the data from CPU to GPU in both cases is high with respective to system bandwidth but GPU still have better performance in comparison to CPU computation. For example, data transfer time for 1×2 and 1×4 antenna systems is 0.8 ms and 1.10 ms respectively, using of 1.25 MHz bandwidth. While in case of 20 MHz it is 7 ms and 10.6 ms, which is quite high besides this, the GPU time is 4.8 ms and 6.5 ms which is less comparison to data transfer time in both the cases. This shows that for large amount of data, GPU is faster at the cost of data transfer time between CPU to GPU. GPU is 4.58 and 6.5 times faster than CPU for 20 MHz bandwidth. Hence, by providing the GPU parallel accelerating support for computationally complex parts of the MIMO-OFDM wireless communication system, the processing time can be reduce significantly.

VI. Conclusion

The complete simulation of IEEE 802.16e WiMAX uplink and downlink system for single user has been carried out under the GPU environment. The simulation model uses the huge computational power of GPU accelerator architecture for most computationally intensive part of the WiMAX uplink and downlink (MRRC-OFDM and STBC-OFDM) systems. The speedup for different FFT points and the speedup for MRRC-OFDM system in case of 1×2 antenna and 1×4 antenna system is presented. The computation throughput of the GPU architecture is shown to outperform the conventional sequential CPU architecture. The GPU is specifically designed to provide the baseband solutions and to make the baseband processing more promising.

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