An Experimental Study of ICI Cancellation in OFDM Utilizing GNU Radio System

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***Abstract*— Inter-Carrier-Interference (ICI) is an effect that noticeably degrades the quality of the Orthogonal Frequency Division Multiplexing (OFDM) signal. In this work, several proposed ICI cancellation schemes have been tested using open source Software Defined Radio (SDR) named GNU Radio. The GNU Radio system used in the experiment had one Universal Software Radio Peripheral (USRP) module connected to a computer. The USRP had two-daughterboard (RFX-400) for both transmission and reception of radio signals in the 400 MHz band. The input data to the USRP was prepared in compliance with IEEE-802.11b specification. The experimental results were compared with the theoretical results of the proposed Inter-Carrier Interference (ICI) cancellation schemes. The comparison of the results revealed that the new schemes are suitable for high performance transmission. The results of this paper open up new opportunities of using OFDM in 400MHz band, where channels are heavily congested. The new ICI cancellation schemes can be used for Digital TV applications or for secured government communication services in the 400MHz to 500MHz band.**

Keywords-OFDM; USRP; GNU radio; ICI cancellation; 400MHz, software defined radio;

I. INTRODUCTION

The OFDM is a technique, where a large number of orthogonal, overlapping subcarriers are transmitted in parallel, dividing the available transmission bandwidth into narrowband sub-channels [1, 2, 3]. The separations of the subcarriers are kept as minimal as possible to get a very compact spectral utilization. Due to the use of narrow bandwidth, each sub channel requires a longer symbol period. The orthogonality of the OFDM is lost when there are channel impairments and frequency mismatch in the transmitter and receiver. This leads to inter-carrier interference, phase rotation and performance degradation of the channel [4]. To reduce the effect of ICI, different cancellation schemes [5, 6] have been proposed and were tested in the GNU radio system. GNU radio is an open source software toolkit for building software radios by making use of software that defines the transmitted waveforms and demodulators instead of hardware components [7].

The paper is organized as follows: Section II illustrates the OFDM modulation and demodulation techniques; Section III describes different ICI cancellation schemes; Section IV explains the need of the experiment, Section V discusses the experimental setup; Section VI explains the binary data preparation; Section VII is about the unique modulation technique used; Section VIII explains software and hardware setup; Section IX describes the data retrieval process; Section X analyses the results; Section XI discusses the future scope of the technology and Section XII makes the concluding remarks.

II. OFDM MODULATION & DEMODULATION

OFDM is a technique as shown in Fig. 1, where the input data is converted to parallel bits and mapped according to predefined standard [9]. Inverse Fast Fourier Transform (IFFT) is a vital part to convert signal from frequency domain to time domain. After IFFT the parallel data is again converted to serial data. Cyclic prefix is also added before it gets converted from digital to analog data. The input data should be prepared maintaining specific standard. According to IEEE-802.11b specification [9], the data is transferred using 64 subcarriers. In the IFFT mapping, the total 64 subcarriers in frequency domain are converted to time domain. In order to preserve the orthogonality of OFDM signal, preamble bits [9] are added. Also the cyclic prefix enables synchronization as the bits are used to detect the beginning and end of each frame and it appends the OFDM symbols one after another [9].

The received signal is demodulated according to the steps shown in Fig. 2, which is the opposite of OFDM modulation technique shown in Fig. 1.

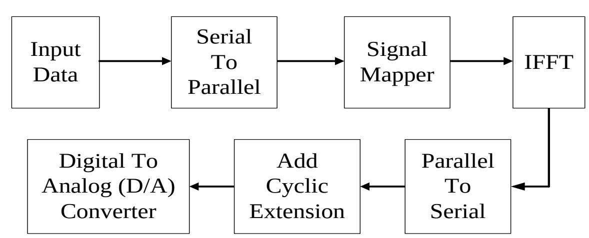

Figure 1. OFDM Modulation

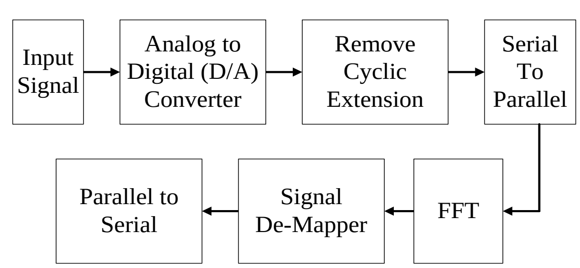

Figure 2. OFDM Demodulation

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III. ICI CANCELLATION SCHEMES

Different cancellation schemes are used in order to reduce the effect of Inter-Carrier-Interference. Among the established models, self-cancellation and modified self-cancellation techniques [11] are considered for the experiment. Also, two other new schemes have been developed and tested during the research [11].

A. ICI self-cancellation

In this scheme each data bit is sent through two adjacent sub-carriers, one with weight '+1' and another with '-1' [11].

$$
\begin{aligned}
Y'(K) &= Y(K) - Y(K+1) \\
&= X(K)[-S(-1) + 2\times S(0) - S(1)] \\
&+ \sum_{\substack{l=0 \\ l\neq even \\ l\neq K}}^{N-2} X(l)[-S(l-K-1) \\
&+ 2\times S(l-K) - S(l-K+1)] \\
&+ [w(K) - w(K+1)] \qquad (1)
\end{aligned}
$$

In order to cancel the ICI at the receiver, adjacent sub-carriers are subtracted, X(K)-(-X(K))=2X(K) [11]. This enhances the data value and reduces the noise level as given in equation (1).

B. ICI modified self-cancellation

In this scheme each data is sent through two sub-carriers one with weight '+1' and another with '-1' [7]. The K^{th} and $(N\text{-}1\text{-}K)^{th}$ subcarriers are used.

$$
\begin{aligned}
Y'(K) &= Y(K) - Y(N-1-K) \\
&= X(K)[2\times S(0) - S(N-1-2K) - S(2K-N+1)] \\
&+ \sum_{\substack{l=0 \\ l\neq K}}^{\frac{N}{2}-1} X(l)[S(l-K) - S(N-1-l-K) \\
&- S(l-N+1+K) + S(-l+K)] \\
&+ \{w(K) - w(N-1-K)\} \qquad (2)
\end{aligned}
$$

Similar to ICI self-cancellation, the interfering components are removed by subtracting the K^{th} and $(N\text{-}1\text{-}K)^{th}$ sub-carriers in the receiving end as shown in equation (2).

C. New ICI cancellation scheme-1

In this scheme each data is sent through four adjacent sub-carriers. The K^{th} and $(K+3)^{th}$ sub-carrier with weight '+1' and $(K+1)^{th}$ and $(K+2)^{th}$ with weight '-1' [1].

$$
\begin{aligned}
Y'(K) &= Y(K) - Y(K+1) - Y(K+2) + Y(K+3) \\
&= X(K)[4\times S(0) - S(1) - 2\times S(2) + S(3) - S(-1) \\
&- 2\times S(-2) + S(-3)] \\
&+ \sum_{\substack{l=0 \\ l=l+4 \\ l\neq K}}^{N-4} X(l)[4\times S(l-K) - S(l-K-1) \\
&- 2\times S(l-K+2) + S(l-K+3) \\
&- S(l-K-1) - 2\times S(l-K-2) + S(l-K-3)] \\
&+ \{w(K) - w(K+1) - w(K+2) + w(K+3) \qquad (3)
\end{aligned}
$$

To retrieve the data at receiving side, 1st and 4th sub-carriers are added and 2nd and 3rd sub-carriers are subtracted as stated in equation (3) [1], X(K)+X(K)-(-X(K))-(-X(K))=4X(K). So the original data values become prominent.

D. New ICI cancellation scheme–2

In this scheme each data bit is sent through four adjacent sub-carriers, each with 90^o phase shift [4]. This gives symmetry to the signal and greatly reduces the effect of the inter carrier interference.

$$
\begin{aligned}
Y'(K) &= Y(K) - e^{-j\frac{\pi}{2}} Y(K+1) - Y(K+2) + e^{-j\frac{\pi}{2}} Y(K+3) \\
&= X(K)\begin{bmatrix} [3\times S(0) - 2\times S(2) - S(-2)] \\ + e^{-j\frac{\pi}{2}}[2\times S(1) - 3\times S(-1) + S(-3)] \\ + e^{j\frac{\pi}{2}}[S(3) - S(1)] + e^{-j\pi}[-S(0) + S(-2)] \end{bmatrix} \\
&\sum_{\substack{l=0 \\ l=l+4 \\ l\neq K}}^{N-4} X(l)\begin{bmatrix} [3\times S(l-K) - 2\times S(l-K+2) - S(l-K-2)] \\ + e^{-j\frac{\pi}{2}}\begin{bmatrix} 2\times S(l-K+1) - 3\times S(l-K-1) \\ + S(l-K-3) \end{bmatrix} \\ + e^{j\frac{\pi}{2}}[S(l-K+3) - S(l-K+1)] \\ + e^{-j\pi}[-S(l-K) + S(l-K-2)] \end{bmatrix} \\
&+ \{w(K) - w(K+1) - w(K+2) + w(K+3)\} \qquad (4)
\end{aligned}
$$

In the receiving end, the 3^{rd} and 4^{th} are phase shifted by 90^o and added to 1^{st} and 2^{nd} sub-carriers respectively. Then the results of 2^{nd} and 4^{th} phases are again shifted by 180^o to get the original data as shown in equation (4).

IV. THE NEED FOR THE EXPERIMENT

In OFDM technique a large number of orthogonal subcarriers are transmitted in parallel dividing the available transmission bandwidth into narrowband sub-channels [1,2, 3]. The separations of the subcarriers are kept as minimal as possible to get a very compact spectral utilization. The channel impairments and frequency mismatch in the transmitter and receiver, sometimes lead to inter-carrier interference (ICI) and phase rotation, resulting in performance degradation of the channel [4]. In order to reduce the effect of ICI, different cancellation schemes [5,6] have been proposed. These schemes help to reduce the effects of ICI by cancelling out the interference from carrier. As the data itself is used to cancel the interference, no extra encoding is needed for error correction. The results from hardware simulations give better insight about the real life problems than does software simulations. The GNU radio is a cost effective and flexible implementation platform that can be used to verify the functionalities as well as the performance of advanced models of wireless technologies in a real time setup. The advent of high speed processors with increased computational capability is making the software and hardware of GNU radio much closer to the antenna. One of the main advantages of SDR is that it is software reconfigurable, which leads to significant design simplification.

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V. EXPERIMENT

In the experiment, an input audio data was modulated using OFDM technique. The setup of the experiment is illustrated in Fig. 3 where initially a recorded audio voice signal was taken and it was imported into MATLAB where all the OFDM processing along with ICI cancellation encoding was performed and the resulting data was sent to a GNU Radio Companion (GRC) running computer. That computer was connected to a USRP transmitter. GNU Radio processed and transmitted the signal over the air. At the other end, an USRP receiver captured the signal, processed in GNU Radio and sent it back to MATLAB. The MATLAB demodulated and decoded the data and regenerated the sound and sent it to the speaker.

VI. BINARY DATA PREPARATION

The steps of preparing binary data in MATLAB are shown in the Fig. 4. In the experiment the input signal was a pre-recorded audio voice signal as shown in Fig. 5. The duration of the audio signal was two seconds and it was sampled at 8 kHz. The signal was compressed using the A-law companding technique [2] with A=80. The signal then quantized using pre-determined step size. In the experiment the step size was 512 in the range of -256 to 255. Then 256 were added to all the quantized values to make it positive integer and the sample quantized. The quantized data then converted into binary string using MATLAB function. The system used 9 bits for each level. With total 512 levels ranges from 0 to 511. The produced data was binary strings. The strings were converted to individual number bits for the use of modulation. The numbers were then modulated either using Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK). In case of BPSK [9], the simplest form of digital modulation technique, the phase of a constant amplitude carrier signal is switched between two values of 1 and 0. The two phases are separated by 180^0. Here all the 0's became -1 and 1's remained as 1. After the BPSK/QPSK modulation, each of the different ICI cancellation schemes (as discussed in section III) were implemented.

VII. MODULATION

Then OFDM modulation was performed according to IEEE-802.11b specification [9] as discussed in section II.

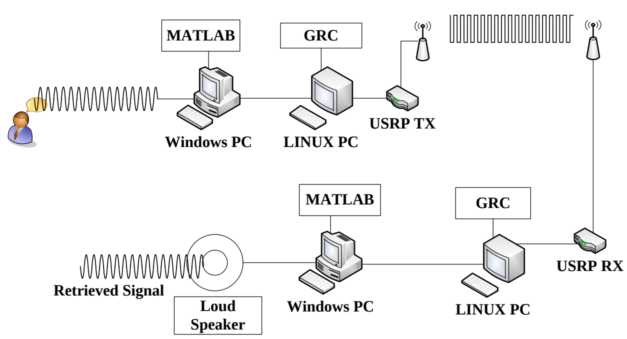

Figure 3. Experimental setup

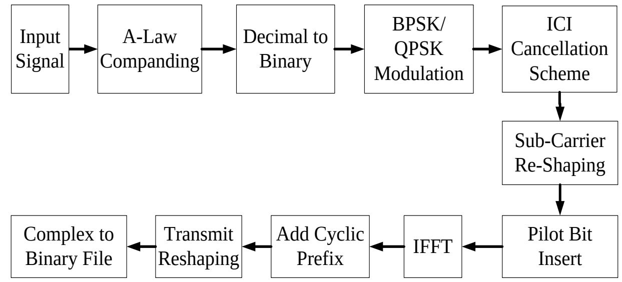

Figure 4. Steps of preparing binary data.

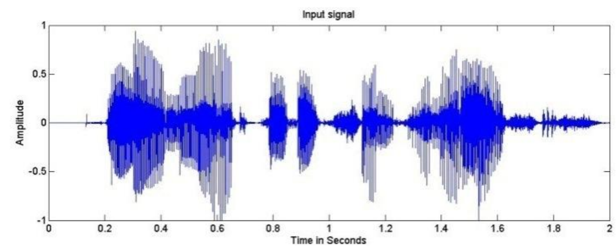

Figure 5. Message signal

Total 52 subcarriers were divided into two groups of 26 bits. A null value was added between the two groups. The subcarrier number 27 to 52 including the null value was placed in front of the signal. The eleven null bits or pilot bits were added, and the rest of the subcarriers were placed after the pilot bits [9]. This made 64 subcarrier long signals as shown in Fig. 6. Here each number denotes subcarrier number.

In the IFFT mapping, the total 64 subcarriers in frequency domain were converted to time domain by IFFT. A 64-point IFFT was used in the experiment. The coefficients 1 to 26 were mapped to the same numbered IFFT inputs, while the coefficients –26 to –1 were copied into IFFT inputs 38 to 63. The rest of the inputs, 27 to 37 and the 0 (dc) input, were set to 0 or null as pilot bits [9]. The IFFT performs the process of transforming a spectrum (amplitude and phase of each component) into a time domain signal. An IFFT converts a number of complex data points of length that is a power of 2, into the time domain signal of the same number of points [9]. After IFFT the signal domain value of 64 subcarriers were placed, where the 49^{th} and 64^{th} subcarrier numbers are copied at the beginning of the signal as preamble as shown in Fig. 7 [9]. The addition of preamble bits allows the orthogonality of OFDM signals to be preserved. The total numbers of bits after a preamble addition was 80 bits. The addition of these bits enables synchronization as the bits were used to detect the beginning and end of each frame appending the OFDM symbols one after another. This was the 80 subcarrier long signal that was transferred. Fig. 8 was the signal that was transmitted. This signal was converted from complex to binary and was saved in a file to be exported to GNU Radio system. A special method was used to make binary conversion where the real and imaginary parts of the complex signals were separated

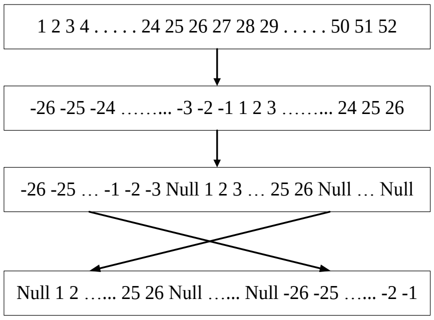

Figure 6. Sub-Carrier Re-Shaping

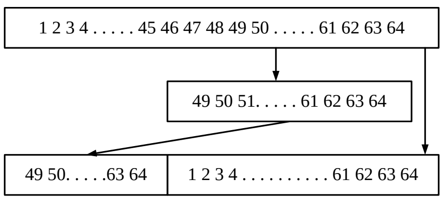

Figure 7. Adding Cyclic Prefix

and written in a file interleaved the data. This way string of real and complex valued signal was mapped in a binary formatted file shown in Fig. 9. The GNU Radio can utilize the file as a source to transmit over the air.

VIII. GNU Radio And Hardware Setup

GNU Radio is an open source software toolkit used for the experiment [7, 8]. In the GNU Radio Companion (GRC) software the file source block was used for feeding the binary file which was passed through a constant multiplier and was transferred to the USRP sink to transmit Over-the-Air (OTA). Fig. 10 illustrates the implementation of the hardware parts of the GNU radio system. The binary file was transferred to the "low cost" hardware called USRP and was passed onto the transmitter daughterboard which are RF frontends. The signal was received by a receiver daughterboard. Similarly, like the transmitter, the signal passed through the receiver USRP and this captured signal was saved in a binary file using the File Sink block [7]. The spectrum can be viewed using the FFT Sink block [7]. All the ICI OFDM BPSK/QPSK modulations were performed in MATLAB and the binary file was extracted from there.

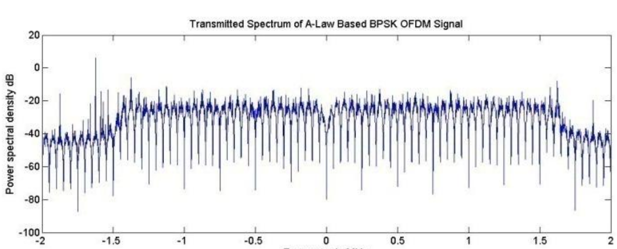

Figure 8. Transmitted Signal

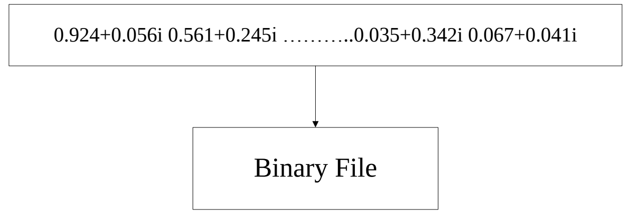

Figure 9. Complex value to Binary File Creation

IX. Data Retrieval

The received binary file was imported to MATLAB and the resulting received spectrum as shown in Fig. 11 was displayed. From the spectrum, densely congested ICI cancellation signal was noticed and also noise components were visible. Fig. 12 is the opposite of the data preparation as shown in Fig. 4. Here the received signal was saved to a binary file. From the binary file, the complex values were extracted, some representative samples are shown in Fig. 13. The 16 bits of cyclic prefix that was added was removed followed by FFT which converts the time domain signal into frequency domain. The subcarrier bits have been extracted from this signal and the 12 pilot bits are removed. Step by step, the ICI cancellation schemes were performed followed by the BPSK/QPSK demodulation as shown in Fig. 12. The data was then converted to binary digits and A-law decompression was implemented and the audio voice signal was regenerated.

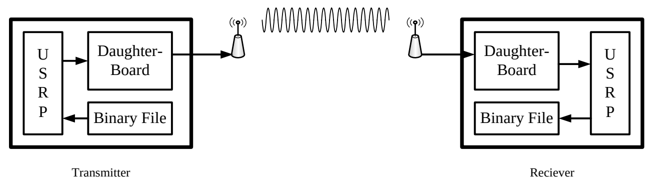

Figure 10. Complex value to Binary File Creation

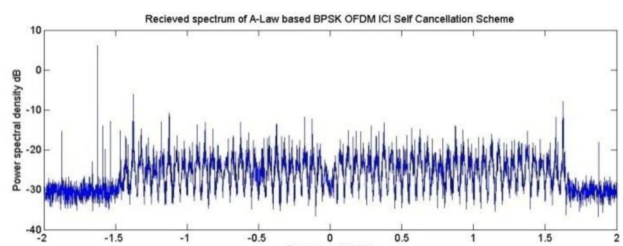

Figure 11. Received Spectrum

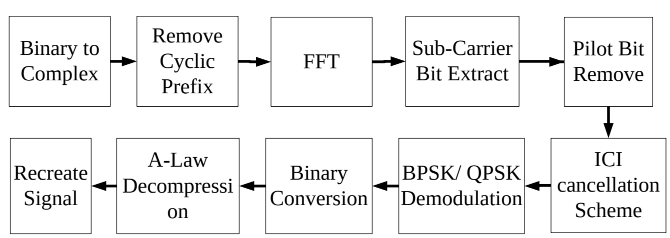

Figure 12. Data Retrieval.

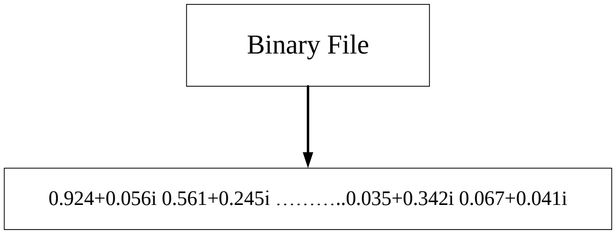

Figure 13. Binary to Complex Conversion

X. RESULT AND ANALYSIS

Fig. 8 shows the transmitted spectrum of the OFDM BPSK signal which was generated in compliance to IEEE specification [9]. The spectrum has 80 sub-carriers according to the standard. There are 16 cyclic prefixes or preamble (8 on each side). The middle portion contains the 64 IFFT data sub-carriers with 12 pilot bits. In total 52 data sub-carriers were embedded in frequency domain [9]. Fig. 11 shows the received spectrum of the same signal at the receiving end. The signal suffered attenuation and inter-carrier-interference (ICI) during transmission. From the figure the effect of Additive White Gaussian Noise (AWGN) noise can be clearly seen by looking at the cyclic prefixes. The visible figure can be said to have dominant noise components. The total power level also decreases significantly. There are many peaks and sudden drops in the spectrum which were not present in the original transmitted spectrum. The effects of ICI are also clearly visible from the figure as the adjacent carriers are almost overlapping. Fig. 14 is the original message signal, which is very nicely shaped and does not have any distortion pattern or sudden peaks or valleys. The received signal, however, is not fully free of noises. So, the reconstructed signal could not be retrieved as such from the received spectrum. Fig. 15 shows the reconstructed signal in time domain. The figure clearly displays the noises and ICI effects on the message. There are many drops across the message. However these problems can be resolved by using the new schemes. Fig. 16 shows received spectrum with ICI new scheme – 1 BPSK OFDM. From the figure it can be deduced that the spectrum has improved from the previous scheme. The regenerated signal also has low distortion. Fig. 17 is the regenerated signal.

In scheme-2, the performance improved a lot. Basically in the test, the scheme-2 was the most efficient signal. In that scheme the retrieved signal was almost same the original signal. From Fig. 18 the improvement in the dense sub-carriers can be easily seen. The improvement is clearly visible in the cyclic prefix and also in the data sub carriers.

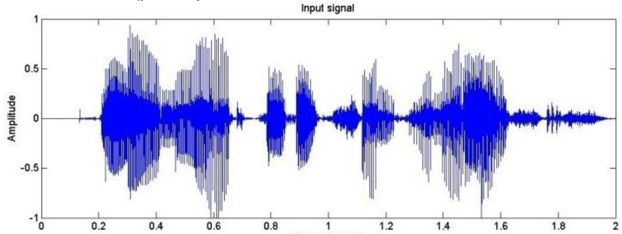

Figure 14. Transmitted Message

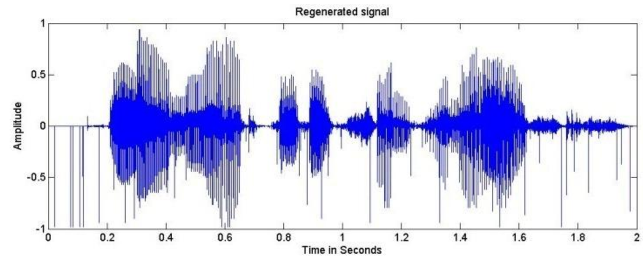

Figure 15. Regenerated ICI-self cancelled signal

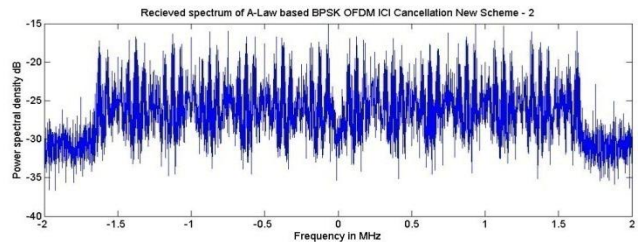

Figure 16. Received Spectrum of New Scheme – 1

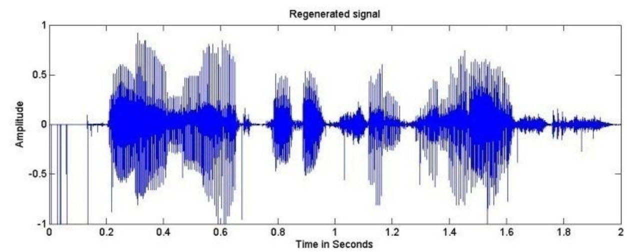

Figure 17. Regenerated New scheme –1 signal

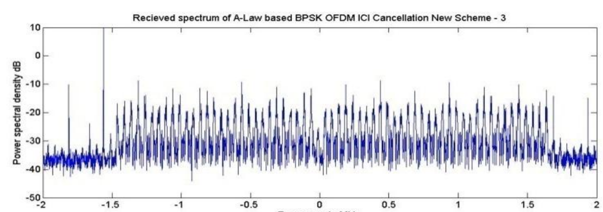

Figure 18. Received Spectrum of New Scheme – 2

The sub carrier signals have retained their original shapes and power level. The signal has not been distorted severely due to AWGN noise and ICI as observed from the spectrum. The regenerated signal also shows the improvement as seen from Fig. 19. There are not many drops in the signal. The regenerated signal is almost 99% close to original signal.

This improvement in the performance justifies the feasibility of the new schemes in OFDM to cancel the ICI and improve performance. The error percentages in new schemes are shown in Table 1 where the new scheme–2 gave the best CIR values. The performance improves because of the symmetrical transmission of the subcarriers.

Though the new schemes improve the performance to a great extent, the bandwidth utilization has not been efficient. Normal OFDM uses full bandwidth of the channel whereas the self-cancellation schemes use only half of it. The new schemes are less efficient with the use of only quarter of the

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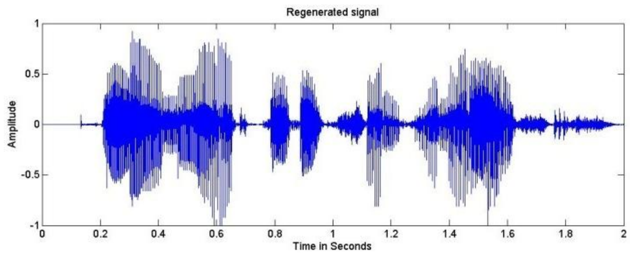

Figure 19. Regenerated signal for New Scheme – 3

TABLE I. ERROR PERFORMANCE

Schemes	Results		
	No. of transmitted bits	***Error bits***	***% bit error***
ICI self	184320	293	0.159%
New scheme -1	184320	171	0.093%
New scheme -2	184320	1	0.00001%

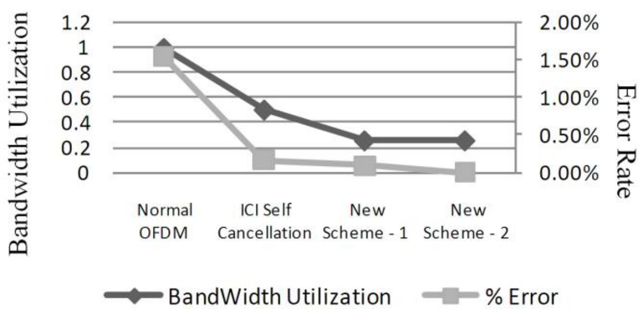

Figure 20. Performance comparison of schemes

bandwidth as shown in Fig. 20. Theoretically, the data rate also decreases and new schemes has almost quarter the data rate than the normal OFDM. If the transmission gives more emphasis on performance and data rate is not a concern, the new schemes are better choice than the already established self-cancellation schemes. The New Schemes also require greater resources to process the cancellation on both transmitter and receiver.

XI. FUTURE SCOPE

The outcome of the research shows the feasibility of the implementation of OFDM in GNU Radio system, which provides a new field to explore. The project was used to verify the viability of the schemes that was considered for testing. Implementing the ICI cancellation scheme gives an opportunity to retrieve signals with better accuracy, so further test can be done using the GNU Radio involving ICI schemes. The availability of the hardware will enable the researchers to perform more practical implementation and hence to obtain more accurate results.

This experiment was conducted in 400 MHz frequency band. Further investigation of the OFDM systems also can be done in 2.4 GHZ or 5GHz frequency bands in the future. The use of OFDM in newer technologies like LTE, WiMAX, Wi-Fi, Digital TV can be tested for practical feasibility in GNU Radio using the techniques used in this experiment. The research also opens up the opportunity to think and explore the options for 400 MHz frequency band similar to the initiatives taken in Australia [11]. The use of OFDM can help utilize the full capacity of this band to a greater extent. The new schemes can be tested in Digital TV services for getting the best possible clarity of the channel.

XII. CONCLUSION

The OFDM system, because of its robustness to multipath fading, has become popular in recent years. The project concentrated on testing the established schemes which were already developed and seemed to have improved the performance of the OFDM system. The schemes included ICI self-cancellation, and modified ICI self-cancellation. The two new schemes as mentioned in reference [10] were also tested in hardware radio transmission. The focus of this project was to check the viability of these schemes. The result shows significant improvements in new schemes. But the inefficient bandwidth utilization and low data rate restrict its use only in high performance systems. The digital HD TV, secured government communication network on 400 MHz band, possibilities of data transfer through amateur radio band, emergency surveillance and rural telephone services [11] can utilize the effectiveness of the new schemes because in terms of performance the new schemes give far better performance than already established ICI cancellation techniques.

ACKNOWLEDGMENT

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