Enhanced MP3 transmission over Wi-Fi and LTE networks using unequal error protection and varying frequency transforms

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ABSTRACT
Wi-Fi and LTE are commonly used for the transmission of high bandwidth data and multimedia over the internet. Providing a good quality of service in the transmission of such data over these wireless channels is challenging due to channel impairments such as noise and fading. This paper proposes three enhanced transmission schemes for audio over Wi-Fi and LTE. The first proposed scheme exploits the unequal importance of the bits generated by an MP3 codec to offer different levels of protection to them during transmission by mapping the important bits on prioritized QAM constellation bit positions. The second and third schemes use the statistical distribution of source symbols to map the bits of the encoded symbols to an SQAM constellation. For the second scheme, only systematic bits from the encoder are mapped onto the SQAM constellation. While for the third scheme, both the systematic and parity bits are mapped onto the SQAM constellation. A comparative analysis with different frequency transforms have been done. The simulation results show that the proposed schemes increase the system performance by 1–20 dB in segmented signal to noise ratio (SSNR). Using DWT further increases the gains up to 90 dB for 16-QAM at rate ½ as compared to FFT.

Introduction
Wireless communication is the fastest growing sector in the communications industry. Over the years, the popularity of wireless networks has grown considerably as they have been widely deployed. Wireless networks are fast, readily available, easily upgraded and compatible with virtually all devices. Wireless local-area networks (WLAN) are becoming a standard part of both home and office networks. Most modern WLANs are based on the IEEE 802.11 standards, more commonly known as Wireless Fidelity (Wi-Fi). Wi-Fi uses radio frequency (RF) technology to provide wireless high-speed Internet and network connections. It does not require any support from the cellular infrastructure. A Wi-Fi router can be connected to a wired broadband connection and access to wireless internet is available. The Wi-Fi router acts as an access point. The primary job of the access point is to
broadcast a wireless signal. Wi-Fi only works within a few metres range from the access point. It uses Orthogonal Frequency-Division Multiple Access (OFDM) for both the downlink and uplink. Another wireless network technology that is gaining momentum is Long-Term Evolution (LTE), which is a wireless broadband communication technology that is highly used for the transmission of data and voice over the internet. LTE is a standard for cellular networks and needs the support of a cellular operator who installs equipment like base stations to work. The distance coverage extends to a few miles. Users are able to use it indoor as well as outdoor. It uses OFDM for the downlink and single-carrier frequency-division multiple access (SC-FDMA) for uplink in order to conserve the power. With Wi-Fi and LTE, users have increased mobility and collaboration, better responsiveness and quick access to information and rich multimedia services such as live audio and video streaming. New mobile devices are able to provide seamless transition from one network to another, thus users are always connected to their streaming applications. According to the IFPI 2018 Music Consumer Insight Report (2018), 86% of consumers listen to music online using on-demand streaming services, resulting in an ever-increasing demand for wireless bandwidth leading to massive stress on wireless networks. Audio streaming and transmission on wireless networks is very strenuous as a definite level of quality of service (QoS) must be maintained. Compressed audio data distribution over wireless networks is extremely challenging as it is significantly susceptible to errors. One transmission error can lead to an unusable string of bits. Transmission delays cannot be tolerated in live audio streaming, making the use of retransmissions limited. Therefore, a number of unequal error protection (UEP) schemes have emerged to enhance multimedia transmission and streaming. An overview of these techniques is given next.

Perera, Fernando, Arachchi, and Imran (2015) proposed a new adaptive modulation and coding based transmission scheme to add adaptive error resilience on high efficiency video coding-based video data at the physical layer for long-term evolution-advanced (LTE-A) networks. Resource elements (REs) were positioned according to channel information at the LTE-A transmitter. To maintain the video quality and increase the efficiency of the users’ allocated bandwidth, data were allocated onto the aligned REs. A stronger modulation and coding scheme was imposed on data having a higher chance of being distorted, thus spanning the entire allocated bandwidth. The proposed UEP strategy helped to decrease the LTE-A transmitter power by up to 8 dB, which was a reduction of approximately 84% of the transmit power, with guaranteed video quality. Studies have showed that inter-layered network coding is a favourable strategy to assign UEP for scalable video multicast under the channel heterogeneity. Optimal transmission distribution selection done at evolved NodeBs enhanced the system performance. A state of the art transmission method for the scalable video multicast using triangular network coding at the application layer in LTE/LTE-advanced networks was investigated by Chau, Lee, Bui, Shin, and Jeong (2016). The proposed transmission scheme consisted of reducing space by using a predictive algorithm and maximizing the performance by reducing the number of searching steps in the dictionary of possible transmission distributions. Results showed that the proposed scheme outperformed other recent studies. A new resource allocation framework for efficient multicasting layered video services was presented by Tassi, Chatzigeorgiou, Vukobratović, and Jones (2015). The targets were to increase service coverage with low radio resource imprint. The reliability of the multicast video services was achieved by a UEP implementation of the network coding (UEP-NC) scheme.
Communication specifications together with the UEP-NC scheme were improved by a resource allocation plan. The proposed allocation framework considerably increased the service coverage. Choi et al. (2016) designed link adaptation policies for the streaming of high-quality ‘uncompressed’ video on the emerging 60-GHz multigigabits per second wireless technology. For a logical design, suitable transmission rates for the 60-GHz wireless channel environment, in order to optimize video quality and resource management, were selected. A new metric and two link adaptation policies with different objectives considering UEP were proposed. Simulation results demonstrated that the new proposed variable represented the level of video quality well. Also, the proposed link adaptation policies enhanced the resource efficiency while achieving acceptable quality of the video streaming. A two-level scheduling scheme for video transmission over downlink orthogonal frequency-division multiple access (OFDMA) networks was proposed by Tham, Chow, Xu, and Ramli (2016). The multiuser diversity and the video characteristics were exploited to increase the combined quality of the video users. For the upper level schedules, the transfer of video packets among multiple users was established by a target bit-error-rate (BER), the importance level of packet and resource consumption efficiency factor. UEP for the lower level was provided in terms of target BER among the scheduled packets by determining a weighted sum distortion minimization problem, where each user weight reflected the total importance level of the packets that has been scheduled for that user. To leverage the potential channel coding gain, frequency-selective power was then water-filled over all the assigned subcarriers. The new scheme provided an increase of up to 6.8 dB in terms of peak-signal-to-noise-ratio over the state-of-the-art scheduling scheme. The use of product code based on a vertical low-density parity check (LDPC) code and horizontal Reed-Solomon (RS) code for transmission of progressively coded image was studied by Majumder and Verma (2016). Multimedia information was encoded with varying RS parity levels depending on the relative importance of symbols in the message stream. Before being OFDM modulated, Cyclic redundancy check (CRC) was added to the RS symbols which were then LDPC coded. The proposed algorithm used the correctly decoded RS coded bits to improve the error correcting capability of LDPC codes. The system performance was tested over different fading channels for OFDM system and the results showed an enhanced performance of the proposed system over existing and baseline schemes. The performance of three-dimensional (3D) audio was improved by using a coding scheme proposed by Su et al. (2015). Joint source channel coding (JSCC) was used to design the scheme and expanding window fountain (EWF) codes for the 3D audio bitstreams was used to implement it after source coding of spatial squeeze surround audio coding (S3AC). EWF is one form of UEP Luby Transform code. Downmixed mono signals and spatial side information was obtained after S3AC coding. More protection was given to the spatial side information and comparatively less protection was given to the downmixed mono signals resulting in the improvement of the performance of the reproduced 3D audio especially on the aspect of the spatial perception. Another UEP scheme for 3D audio was proposed by Yang et al. (2017). In this paper, the important audio object was extracted and was given more protection than the normal audio objects. Both objective and subjective results showed that the UEP method achieved better performance than the equal error protection (EEP) one. The BER decreased from $10^{-3}$ to $10^{-4}$ and the subjective quality of UEP was 14% better than that of EEP. Nguyen and Nguyen (2016) developed a dynamic adaptation algorithm of joint source–channel code rate for enhancing voice transmission over LTE
network. The wideband E-model was used to assess the speech quality. The aim of the work was to find out the best suboptimal solution for improving voice traffic over LTE network with some constraints on allowed maximum end-to-end delay, allowed maximum packet loss and minimum required bandwidth. The best suboptimal choice was a channel code rate corresponding to each mode of the adaptive multi-rate wideband codec that decreased the redundant bits generated by channel coding with an acceptable mean opinion score (MOS) reduction. Results showed that the MOS degradation was not significant but the percentage of reduced redundant bits was considerable.

An enhanced audio transmission scheme with two levels of UEP for MP3 over LTE was presented by Ragpot, Fowdur, and Soyjaudah (2017). For the first level of UEP, the unequal importance of the bits generated by an MP3 codec was exploited, that is they were divided into control information bits and scalefactor and subbands bits. For the second level, the varying importance of the bitstreams generated by a turbo encoder was used. The turbo encoded bits were separated in systematic and parity bits. The different bitstreams were given different level of protection during LTE transmission by positioning the bits in such a way so that the more important ones are given more protection than the least important bits. Simulation was done in fast Fourier transform (FFT) domain only. Results showed that with 16-quadrature amplitude modulation (QAM) at a turbo code rate of 1/2, the proposed two level UEP scheme provided a gain of 22.36 dB in average in SSNR over a conventional EEP one. This paper builds up on the work by Ragpot et al. (2017) by investigating a new UEP scheme with prioritized QAM constellations mapping and two other UEP schemes exploiting the statistical distribution of the source symbols to map systematic bits onto QAM constellations. The MP3 compressed audio files are transmitted using both LTE and Wi-Fi systems. Hence, both LTE Turbo codes and LDPC codes have been used and integrated into the UEP schemes to exploit the difference in importance of their systematic and parity bits. Moreover, two variants of the DWT have been used to provide better gains than that obtained by FFT.

The paper is organized as follows. A detailed explanation of the complete system model is given in the second section. The simulation results are thoroughly analysed in the third section and the paper is concluded in the fourth section.

**System model**

The system model of the transmitter was implemented as shown in Figure 1.

On the transmitter side, an uncompressed audio file is sent to the MP3 encoder which consists of the different signal processing blocks. These consist of FFT, 32 channel polyphase analysis filterbank, psychoacoustic analysis, modified discrete cosine transform (MDCT) adaptive segmentation, bit allocation, code side info and a multiplexer (Thiagarajan & Spanias, 2012). The control information bits (CB) and the scalefactor and subband sample bits (SSB) form an MP3 frame. The MP3 bitstream is then sent to the Encoding, Bit Separation, Bit Reordering and Constellation mapping block where they are encoded, separated according to their importance, reordered and mapped on the constellation being used in the AWGN channel.

On the receiver side, the received bits are demapped, reordered, merged and decoded before being sent to the MP3 decoder. In the MP3 decoder, the bits go through a series of signal processing blocks such as Synchronization and Error Check, Huffman Decoding,
Scalefactor decoding, Requantisation, Reordering, Alias Reduction, Inverse MDCT (IMDCT), frequency inversion and Synthesis Polyphase Filterbank so that the audio file can be reconstructed (Thiagarajan & Spanias, 2012). The receiver system model was implemented as shown in Figure 2.

**Figure 1.** The transmitter system model.

**UEP and encoding**

The control information bits (CB) have a relatively higher importance than the scalefactor and subband sample bits (SSB), thus the MP3 frame bits are separated into two bitstream. The CB bitstream consists of the control information bits while the SSB bitstream consists of
the scalefactor and subband sample bits. Both bitstreams are then encoded. For Wi-Fi, LDPC is used to encode the bitstreams and for LTE, Turbo codes are used. The encoded bitstreams are further divided into systematic bits and parity bits, to exploit the UEP property.

**Bit reordering and constellation mapping**

**Prioritised constellation mapping**

In a 16-QAM constellation as shown in Figure 3, the first and third bits are the same in all four quadrants and they are the most protected one. Thus, the encoded systematic and parity bits are ordered in such a way that the encoded systematic bits are mapped onto the first and third bits position and the parity bits are positioned on the second and fourth bits position (Fowdur, Beeharry, & Soyjaudah, 2013). On the decoder side, if the first and third bits are correctly decoded, the correct quadrant is detected therefore the correct systematic bits are decoded.

For 64-QAM given in Figure 4, the first and fourth bits are the most protected. The second and fifth bits have medium protection while the third and sixth bits are the least protected. The reason is that a 64-QAM constellation has four major quadrants in which the first and fourth bits are the same. Each major quadrant is further divided into four minor quadrants. The minor quadrants are distinguished using the second and fifth bits of the constellation points. The first and fourth bits of the 64-QAM constellation are correctly de-mapped if the de-mapper correctly distinguishes between the four major quadrants. The four minor quadrants in any major quadrant are determined by the correct decoding of the second and fifth bits (Fowdur et al., 2013).

**Constellation mapping with statistical QAM (SQAM)**

SQAM make use of the statistical distribution of the source symbols to map the encoded systematic bits to the QAM constellation. The systematic symbols having highest
possibilities of occurring are mapped onto the low power region of the QAM constellation. Those with low probabilities of occurrence are mapped onto the high power region. As a consequence, the spacing between the constellation points can be increased for the same average energy, hence reducing the overall power required for transmission. In addition, the parity bits having the highest degrees are mapped onto the QAM constellation using the distribution of bit node degrees.

Two hybrid schemes are being proposed. In Hybrid 1, only the systematic bits are mapped onto the SQAM constellation while the parity bits are mapped on the conventional QAM constellation. For Hybrid 2, both the systematic and parity bits are mapped onto the SQAM constellation.

The first step is to determine the a-priori probabilities of QAM symbols using the a-priori probabilities of the systematic bits 1 and 0 and the law of total probabilities. The a-priori probabilities for the two audio files used is given in Table 1.

When 16QAM is used, the bits are grouped into symbols of 4 bits. The a-priori probabilities of each symbol is calculated using:

$$p(\text{symbol}) = \prod (\text{probability of each bit in the symbol})$$

(1)

For example, \(p(1111) = p(1) \times p(1) \times p(1) \times p(1) = 0.0198\)

The probabilities for all the symbols for 16QAM are given in Table 2.
Using the probability of each message symbols, the SQAM transformation table is generated so that the symbols with highest probabilities are allocated to lowest power symbols and the symbols with lowest probabilities are allocated to highest power symbols.

For the transformation, the probability of occurrence of each symbol is considered. Symbols with high probability of occurrence are mapped onto high power points whereas symbols of low probability are mapped onto low power points. From Table 2, it can be seen that the symbol 0000 has a high probability of occurrence thus it is mapped onto 1111 which is a low power symbol. These changes help to reduce the overall transmission power. To maintain the UEP characteristic of the QAM constellation, the bits are flipped instead of interchanging the constellation point positions. Table 2 has been used for both LTE and Wi-Fi. The statistically modified message is then encoded.

The parity bits for the LDPC encoded bits are reordered so that they can take advantage of UEP due to prioritized mapping in the QAM constellation. The reordering is done

**Figure 4.** 64-QAM constellation.

**Table 1.** A-priori probabilities for the two audio files used.

| Audio file number | p(0)     | p(1)     |
|-------------------|----------|----------|
| 1                 | 0.6251   | 0.3749   |
| 2                 | 0.6916   | 0.3084   |
according to the degree distribution of parity bit nodes. The degree of a node is defined as the total number of edges linked to the node, which is also equal to the number of 1s in the column of the parity check matrix corresponding to that bit node. To apply UEP to the parity bits, bits node having higher degrees are given more protection the one with lower degrees. Thus they are placed on prioritized constellation points (Zhang, Li, & Yang, 2016). No UEP can be applied to the Turbo encoded parity bits.

Two hybrid schemes – Hybrid 1 and Hybrid 2, have been used with SQAM and both were implemented using the process explained by Fowdur and Indoonundon (2017). For Hybrid 1, the systematic bits are modulated using SQAM and the parity bits are modulated using the conventional Gray-coded QAM after the reordering process. For the Hybrid 2 system, both the systematic and parity bits are multiplexed and modulated using the SQAM constellation instead of the conventional one. The overall performance is enhanced as the parity bits also are able to benefit from the increased constellation point spacing in the SQAM constellation.

The separation between the neighbouring symbols, $d_s$, for Hybrid 1 and Hybrid 2 is calculated using the process detailed by Fowdur and Indoonundon (2017). The constellation points for the SQAM scheme are then obtained using the value of $d_s$ and the increased spacing between them improves the system performance. Table 3 contains the values of $d_s$ obtained for 16 and 64-QAM for the Hybrid 1 scheme for both audio files for LTE and Wi-Fi. For Hybrid 2, the values obtained are as given in Table 4 for LTE Turbo Codes and Table 5 for LDPC Codes.

### Table 2. SQAM transformation lookup table for both audio files.

| Initial symbol | Audio file 1 | | Audio file 2 |
|---------------|--------------|-----------------|--------------|
|               | 1            | 2               |               |
| 0000          | 0.1527       | 0.2288          | 1111          |
| 0001          | 0.0916       | 0.1020          | 0111          |
| 0010          | 0.0916       | 0.1020          | 1101          |
| 0011          | 0.0549       | 0.0455          | 1000          |
| 0100          | 0.0916       | 0.1020          | 0101          |
| 0101          | 0.0549       | 0.0455          | 0110          |
| 0110          | 0.0549       | 0.0455          | 1001          |
| 0111          | 0.0329       | 0.0203          | 0100          |
| 1000          | 0.0916       | 0.1020          | 1011          |
| 1001          | 0.0549       | 0.0455          | 0011          |
| 1010          | 0.0549       | 0.0455          | 1100          |
| 1011          | 0.0329       | 0.0203          | 1010          |
| 1100          | 0.0549       | 0.0455          | 0010          |
| 1101          | 0.0329       | 0.0203          | 0001          |
| 1110          | 0.0329       | 0.0090          | 0000          |
| 1111          | 0.0198       | 0.0090          | 0000          |

### Table 3. Calculated $d_s$ values for Hybrid 1 for turbo codes and LDPC codes.

| Audio file number | QAM order($M$) | $d_s$ |
|------------------|----------------|------|
| 1                | 16             | 2.52 |
|                  | 64             | 2.84 |
| 2                | 16             | 2.57 |
|                  | 64             | 2.58 |
The code words are then transmitted over an Additive White Gaussian Noise (AWGN) channel.

**Discrete transforms**

Discrete transforms are used to transform signals between discrete time and discrete frequency. In the different schemes, two transforms have been used: FFT and DWT, namely Haar wavelet and Biorthogonal wavelet (Mathsworks, n.d.).

For FFT, the transfer from one domain to another is done using the following equations:

To frequency domain:

\[
X(k) = \sum_{n=0}^{N-1} x(n) \left( \cos \frac{2\pi kn}{N} + i \sin \frac{2\pi kn}{N} \right), \quad k \in Z
\]  

From frequency domain:

\[
x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X_k \left( \cos \frac{2\pi kn}{N} + i \sin \frac{2\pi kn}{N} \right), \quad n \in Z
\]

where \(N\) is the number of samples, \(n\) is the current sample, \(x(n)\) is the value of the signal at time \(n\), \(k\) is the current frequency and \(X(k)\) is the amount of frequency \(k\) in the signal.

The following equation was used to move from time domain to frequency domain for DWT.

\[
X[j, k] = x, \quad \psi[j, k] = \sum_{n=0}^{N-1} x[n] \psi[j, n] \quad j = 0, \ldots, J - 1, \quad k = 0, \ldots, 2^j - 1
\]

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**Table 4.** Calculated \(d_s\) values for Hybrid 2 for turbo codes.

| Audio file number | QAM order \(M\) | Code rate | \(d_s\) |
|------------------|----------------|-----------|--------|
| 1                | 16             | 1/3       | 2.16   |
|                  |                | 1/2       | 2.24   |
|                  | 64             | 1/3       | 2.29   |
|                  |                | 1/2       | 2.41   |
| 2                | 16             | 1/3       | 2.24   |
|                  |                | 1/2       | 2.12   |
|                  | 64             | 1/3       | 2.41   |
|                  |                | 1/2       | 2.31   |

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**Table 5.** Calculated \(d_s\) values for Hybrid 2 for LDPC codes.

| Audio file number | QAM order \(M\) | Code rate | \(d_s\) |
|------------------|----------------|-----------|--------|
| 1                | 16             | 1/2       | 2.24   |
|                  |                | 2/3       | 2.33   |
|                  |                | 3/4       | 2.38   |
|                  | 64             | 1/2       | 2.41   |
|                  |                | 2/3       | 2.54   |
|                  |                | 3/4       | 2.61   |
| 2                | 16             | 1/2       | 2.12   |
|                  |                | 2/3       | 2.20   |
|                  |                | 3/4       | 2.26   |
|                  | 64             | 1/2       | 2.31   |
|                  |                | 2/3       | 2.40   |
|                  |                | 3/4       | 2.44   |
where $j$ is the scale parameter, $k$ is the shift parameter, $x$ is the input signal, $\psi$ is the mother wavelet.

The code words are assumed to be in the frequency domain. On the transmitter side, the inverse of the transforms, IFFT and IDWT are applied to the code words which are then placed on their respective carriers and combined together. FFT and DWT are used on the receiver side.

**Receiver**

For the scheme with the prioritized constellation mapping, the received QAM symbols are de-multiplexed into systematic and parity bits and both are demodulated using the conventional QAM demodulator.

For Hybrid 1, the received QAM symbols are de-multiplexed into systematic and parity bits. The systematic bits are demodulated using the SQAM demodulator while the parity bits are demodulated using the conventional QAM demodulator. For Hybrid 2, the received QAM symbols are demodulated using the SQAM demodulator which are then de-multiplexed into systematic and parity bits.

**Simulation results and analysis**

In all schemes, two audio files have been used with AWGN as channel model. The parameters of the audio files are in Table 6.

For Wi-Fi with LDPC codes, three different code rates – $\frac{1}{2}$, $\frac{2}{3}$ and $\frac{3}{4}$ at a code length of 648 have been used. For LTE with Turbo codes, two different code rates – $\frac{1}{2}$ and $\frac{1}{3}$ with a packet size of 3072 have been used. Since the performance of audio transmission is being evaluated, SSNR is used as a measure. The average SSNR gain is calculated for the different $E_b/N_0$ range used.

The performances of the following schemes are analysed:

- **Scheme 1-FFT**: Conventional MP3 transmission with FFT
- **Scheme 2-FFT**: MP3 transmission with prioritized constellation mapping with FFT
- **Scheme 3-FFT**: MP3 transmission with Hybrid 1 and FFT
- **Scheme 4-FFT**: MP3 transmission with Hybrid 2 and FFT
- **Scheme 1-DWTHAAR**: Conventional MP3 transmission with DWT – Haar wavelet
- **Scheme 2-DWTHAAR**: MP3 transmission with prioritized constellation mapping with DWT – Haar wavelet
- **Scheme 3-DWTHAAR**: MP3 transmission with Hybrid 1 and DWT – Haar wavelet
- **Scheme 4-DWTHAAR**: MP3 transmission with Hybrid 2 and DWT – Haar wavelet
- **Scheme 1-DWTBIOR**: Conventional MP3 transmission with DWT – Biorthogonal wavelet
- **Scheme 2-DWTBIOR**: MP3 transmission with prioritized constellation mapping with DWT – Biorthogonal wavelet

| Table 6. Audio file 1 and file 2 parameters. |
|----------------------------------------------|
| Parameters | File 1  | File 2  |
| Rate/kHz    | 44.1    | 44.1    |
| Size/kbits  | 95      | 107     |
| Maximum SSNR/dB | 153.38 | 168.19  |
Scheme 3-DWTBIOR: MP3 transmission with Hybrid 1 and DWT – Biorthogonal wavelet
Scheme 4-DWTBIOR: MP3 transmission with Hybrid 2 and DWT – Biorthogonal wavelet

The average SSNR gain in dB for each transform is calculated using the following equation:

\[
\text{Average gain in dB in transform} = \frac{\text{Sum of all SSNR values}}{\text{Number of SSNR values}}
\]  

(5)

For example, the average SSNR gain in dB for Scheme 2-DWTBIOR with rate ½ with Wi-Fi for the first audio file is calculated as follows:

Average gain in dB for Scheme 2 – DWTBIOR

\[-8.74 - 6.30 - 2.01 + 10.90 + 41.58 + 92.65 + 133.36 + 153.60 + 162.81 + 164.97 +
167.13 + 167.86 + 168.19 + 168.19 + 168.19 + 168.19 + 168.19 + 168.19 + 168.19 +
168.19 + 168.19 + 168.19 + 168.19\]

\[= \frac{22}{22}\]

\[= 125.44 \text{ dB}\]

To compute the average gain in dB between each scheme or transform, the equation given below is used.

\[
\text{Average gain in dB between schemes/transforms} = \frac{\text{Average gain in dB in first scheme/transform}}{\text{Average gain in dB in second scheme/transform}}
\]  

(6)

For example, the average SSNR gain in dB between Scheme 2-FFT and Scheme 2-DWTBIOR for rate ½ with Wi-Fi for the first audio file is calculated as follows:

\[
\text{Average gain in dB} = \frac{\text{Average gain in Scheme 2 – DWTBIOR}}{\text{Average gain in Scheme 2 – FFT}} - 125.44 - 34.84 = 90.6 \text{ dB}
\]

**Results with 16-QAM for MP3 transmission with LTE**

**Results with first audio file**
The graph of SSNR against Eb/N0 at a rate of 1/3 for the range of 1.25 dB ≤ Eb/N0 ≤ 3 dB is given in Figure 5. The average gains of the different schemes over the conventional one are summarized in Tables 7 and 8. As can be observed from Table 7, the highest gain is achieved with Scheme 4 which provides an average gain of over 9 dB over Scheme 1 with all three transforms. From Table 8, it can be noted that the use of DWT increases the system gain by at least 73 dB when compared to FFT.

The graph of SSNR against Eb/N0 at a rate of 1/2 for the range of 2.5 dB ≤ Eb/N0 ≤ 4.5 dB is given in Figure 6. Tables 9 and 10 summarize the average gains of the different schemes over the conventional one. From Table 9, it can be noted that Scheme 4 surpasses Scheme 1 by at least 14 dB for all three transforms. Replacing FFT with DWT increases the gain of the system by 63 dB, as recorded in Table 10.
Results with second audio file

Same schemes are tested using the second audio file and the results followed the same trend as for the first audio file. A rate of 1/3, a gain of at least 8 dB on average is obtained by Scheme 4 over Scheme 1 for all three transforms. Replacing FFT with DWT yields an average gain of 70 dB. With a rate of ½, for all three transforms Scheme 4 yields 13 dB on average over Scheme 1. The schemes with DWT exceed the schemes with FFT by an average of at least 59 dB.

Results with 64-QAM for MP3 transmission with LTE

Results with first audio file

Figure 7 shows the graph of SSNR against $E_b/N_0$ at a rate of 1/3 for the range of 3 dB $\leq E_b/N_0 \leq 9$ dB. Tables 11 and 12 summarize the average gains of the different schemes over the conventional one. As can be observed from Table 11, a gain of at least 58 dB on average is obtained by Scheme 4 over Scheme 1 for all three transforms. From Table 12, it can be seen that using DWT with the schemes outperform the schemes using FFT by an average of 18 dB.

The graph of SSNR against $E_b/N_0$ at a rate of 1/2 for the range of 3 dB $\leq E_b/N_0 \leq 12.5$ dB is given in Figure 8. The average gains of the different schemes over the conventional one

Table 7. Average gain in dB in each transform.

| Schemes            | FFT  | DWT Haar | DWT Biorthogonal |
|--------------------|------|----------|------------------|
| Scheme 1 & Scheme 2| 6.75 | 1.49     | 2.37             |
| Scheme 1 & Scheme 3| 6.29 | 3.69     | 4.38             |
| Scheme 1 & Scheme 4| 10.71| 9.52     | 10.05            |
| Scheme 2 & Scheme 3| 0.46 | 2.20     | 2.01             |
| Scheme 2 & Scheme 4| 3.96 | 8.02     | 7.68             |
| Scheme 3 & Scheme 4| 4.42 | 5.83     | 5.67             |
are summarized in Tables 13 and 14. As can be observed from Table 13, for all three transforms Scheme 4 yields 75 dB on average over Scheme 1. From Table 14, it can be seen that the schemes with DWT exceed the schemes with FFT by an average of at least 10 dB.

Results with second audio file
With the second audio file at rate 1/3, it is noted that Scheme 4 surpasses Scheme 1 by at least 58 dB for all three transforms. Replacing FFT with DWT increases the gain of the system by 19 dB. With rate ½, the highest gain is achieved with Scheme 4 which provides an average gain of over 64 dB over Scheme 1 with all three transforms. It is noted that the use of DWT increases the system gain by at least 12 dB when compared to FFT.

Results with 16-QAM for MP3 transmission with Wi-Fi

Results with first audio file
The graph of SSNR against $E_b/N_0$ at a rate of ½ for the range of $1.4 \leq E_b/N_0 \leq 5.6$ dB is given in Figure 9. The average gains of the different schemes over the conventional one are summarized in Tables 15 and 16. As can be observed from Table 15, for all three transforms Scheme 4 yields 22 dB on average over Scheme 1. From Table 16, it can be seen that the schemes with DWT exceed the schemes with FFT by an average of at least 85 dB.

| Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
|----------|----------|----------|----------|----------|----------|----------|----------|
| FFT      | 78.41    | –        | –        | 77.64    | –        | –        | –        |
| DWT Haar | 73.14    | 75.81    | 77.21    | 73.26    | 75.73    | 76.97    |
| DWT Biorthogonal | 73.26 | 75.73 |

Figure 6. Graph of SSNR against $E_b/N_0$ at rate ½.
The graph of SSNR against $E_b/N_0$ at a rate of $2/3$ for the range of $2.4 \text{ dB} \leq E_b/N_0 \leq 6.8 \text{ dB}$ is given in Figure 10. A summary of the average gains of the different schemes over the conventional one is given in Tables 17 and 18. As can be observed from Table 17, a gain of at least 18 dB on average is obtained by Scheme 4 over Scheme 1 for all three transforms. From Table 18, it can be seen that using DWT with the schemes outperform the schemes using FFT by an average of 79 dB.

The graph of SSNR against $E_b/N_0$ at a rate of $3/4$ for the range of $3.6 \text{ dB} \leq E_b/N_0 \leq 7.6 \text{ dB}$ is given in Figure 11. Tables 19 and 20 summarize the average gains of the different schemes over the conventional one. From Table 19, it can be noted that Scheme 4 surpasses Scheme 1 by at least 2 dB for all three transforms. Replacing FFT with DWT increases the gain of the system by 83 dB, as recorded in Table 20.

**Table 9.** Average gain in dB in each transform.

| Schemes       | FFT  | DWT Haar | DWT Biorthogonal |
|---------------|------|----------|------------------|
| Scheme 1 & Scheme 2 | 8.44 | 2.91     | 3.51             |
| Scheme 1 & Scheme 3 | 20.18| 14.73    | 15.11            |
| Scheme 1 & Scheme 4 | 19.92| 14.99    | 14.74            |
| Scheme 2 & Scheme 3 | 11.74| 11.82    | 11.59            |
| Scheme 2 & Scheme 4 | 11.48| 12.08    | 11.22            |
| Scheme 3 & Scheme 4 | 0.26 | 0.26     | 0.37             |

**Table 10.** Average gain in dB between FFT and DWT transforms.

| FFT | DWT Haar | DWT Biorthogonal |
|-----|----------|------------------|
|     | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
| Scheme 1 | 69.46   | –       | –       | –       | 69.20    | –       | –       | –       |
| Scheme 2 | –       | 63.93   | –       | –       | 64.27    | –       | –       | –       |
| Scheme 3 | –       | –       | 64.01   | –       | –       | 64.13   | –       | –       |
| Scheme 4 | –       | –       | –       | 64.53   | –       | –       | 64.02   | –       |

![Graph of SSNR against $E_b/N_0$](image.png)
Table 11. Average gain in dB in each transform.

| Schemes                  | FFT  | DWT Haar | DWT Biorthogonal |
|--------------------------|------|----------|------------------|
| Scheme 1 & Scheme 2      | 37.19| 30.23    | 30.62            |
| Scheme 1 & Scheme 3      | 65.32| 57.50    | 57.71            |
| Scheme 1 & Scheme 4      | 70.72| 58.52    | 59.03            |
| Scheme 2 & Scheme 3      | 28.13| 27.27    | 27.09            |
| Scheme 2 & Scheme 4      | 33.52| 28.29    | 28.40            |
| Scheme 3 & Scheme 4      | 5.40 | 1.02     | 1.31             |

Table 12. Average gain in dB between FFT and DWT transforms.

| FFT          | DWT Haar | DWT Biorthogonal |
|--------------|----------|------------------|
| Scheme 1     |          | –                |
| Scheme 2     | 30.73    | –                |
| Scheme 3     | –        | 23.77            |
| Scheme 4     | –        | 22.91            |

Figure 8. Graph of SSNR against $E_b/N_0$ at rate $\frac{1}{2}$.

Table 13. Average gain in dB in each transform.

| Schemes                  | FFT  | DWT Haar | DWT Biorthogonal |
|--------------------------|------|----------|------------------|
| Scheme 1 & Scheme 2      | 18.85| 10.51    | 8.96             |
| Scheme 1 & Scheme 3      | 74.01| 75.35    | 73.32            |
| Scheme 1 & Scheme 4      | 77.84| 101.81   | 75.97            |
| Scheme 2 & Scheme 3      | 55.16| 64.84    | 64.37            |
| Scheme 2 & Scheme 4      | 58.99| 91.30    | 67.01            |
| Scheme 3 & Scheme 4      | 3.82 | 26.45    | 2.64             |
Table 14. Average gain in dB between FFT and DWT transforms.

|                | DWT Haar | DWT Biorthogonal |
|----------------|----------|------------------|
|                | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
| Scheme 1       | 19.03    | –        | –        | –        | 20.83    | –        | –        | –        |
| Scheme 2       | –        | 10.69    | –        | –        | –        | 10.94    | –        | –        |
| Scheme 3       | –        | –        | 20.38    | –        | –        | –        | 20.14    | –        |
| Scheme 4       | –        | –        | –        | 43.00    | –        | –        | –        | 18.96    |

Figure 9. Graph of SSNR against $E_b/N_0$ at rate $\frac{1}{2}$.

Table 15. Average gain in dB in each transform.

| Schemes                  | Average gain (dB) in transforms |
|--------------------------|----------------------------------|
|                          | FFT   | DWT Haar | DWT Biorthogonal |
| Scheme 1 & Scheme 2      | 6.55  | 8.97     | 9.92             |
| Scheme 1 & Scheme 3      | 19.76 | 18.66    | 18.78            |
| Scheme 1 & Scheme 4      | 23.89 | 22.55    | 22.55            |
| Scheme 2 & Scheme 3      | 13.21 | 9.69     | 8.86             |
| Scheme 2 & Scheme 4      | 17.34 | 13.58    | 12.63            |
| Scheme 3 & Scheme 4      | 4.13  | 3.89     | 3.77             |

Table 16. Average gain in dB between FFT and DWT transforms.

|                | DWT Haar | DWT Biorthogonal |
|----------------|----------|------------------|
|                | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
| Scheme 1       | 87.27    | –        | –        | –        | 87.24    | –        | –        | –        |
| Scheme 2       | –        | 89.69    | –        | –        | –        | 90.61    | –        | –        |
| Scheme 3       | –        | –        | 86.17    | –        | –        | –        | 86.26    | –        |
| Scheme 4       | –        | –        | –        | 85.93    | –        | –        | –        | 85.90    |
Results with second audio file

Same schemes are tested using the second audio file and the results followed the same trend as for the first audio file. At rate $\frac{1}{2}$, the highest gain is achieved with Scheme 4 which provides an average gain of over 22 dB over Scheme 1 with all three transforms. It is noted that the use of DWT increases the system gain by at least 79 dB when compared to FFT. With a rate of $\frac{2}{3}$ for all three transforms, Scheme 4 yields 18 dB on average over Scheme 1. It is observed that the schemes with DWT exceed the schemes with FFT by an average of at least 73 dB. With a rate of $\frac{3}{4}$, the highest gain is achieved with Scheme 4 which provides an average gain of over 2 dB over Scheme 1 with all three transforms. It is noted that the use of DWT increases the system gain by at least 84 dB when compared to FFT.

### Table 18. Average gain in dB between FFT and DWT transforms.

| FFT         | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | DWT Haar | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | DWT Biorthogonal | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
|-------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-------------------|----------|----------|----------|----------|
| Scheme 1    | 79.57    | –        | –        | –        | 79.60    | –        | –        | –        | –        | –                 | –        | –        | –        | –        |
| Scheme 2    | –        | 81.34    | –        | –        | 81.21    | –        | –        | –        | –        | –                 | –        | –        | –        | –        |
| Scheme 3    | –        | –        | 83.13    | –        | –        | –        | 82.85    | –        | –        | –                 | –        | –        | 82.57    | –        |
| Scheme 4    | –        | –        | –        | 83.06    | –        | –        | –        | –        | –        | –                 | –        | 82.57    | –        | –        |
Results with 64-QAM for MP3 transmission with Wi-Fi

Results with first audio file
The graph of SSNR against $E_b/N_0$ at a rate of $\frac{1}{2}$ for the range of $4 \, dB \leq E_b/N_0 \leq 14 \, dB$ is given in Figure 12. The average gains of the different schemes over the conventional one are summarized in Tables 21 and 22. From Table 21, it can be noted that Scheme 4 surpasses Scheme 1 by at least 48 dB for all three transforms. Replacing FFT with DWT increases the gain of the system by 36 dB, as recorded in Table 22.

The graph of SSNR against $E_b/N_0$ at a rate of $\frac{2}{3}$ for the range of $6 \, dB \leq E_b/N_0 \leq 15.2 \, dB$ is given in Figure 13. Tables 23 and 24 summarize the average gains of the different schemes over the conventional one. As can be observed from Table 23, a gain of at least 72 dB on average is obtained by Scheme 4 over Scheme 1 for all three transforms. From Table 24, it can be seen that using DWT with the schemes outperform the schemes using FFT by an average of 40 dB.

The graph of SSNR against $E_b/N_0$ at a rate of $\frac{3}{4}$ for the range of $6.8 \, dB \leq E_b/N_0 \leq 16.4 \, dB$ is given in Figure 14. The average gains of the different schemes over the conventional one are summarized in Tables 25 and 26. As can be observed from Table 25, for all three transforms Scheme 4 yields 53 dB on average over Scheme 1. From Table 26, it can be seen that the schemes with DWT exceed the schemes with FFT by an average of at least 38 dB.

Table 19. Average gain in dB in each transform.

| Schemes              | FFT  | DWT Haar | DWT Biorthogonal |
|----------------------|------|----------|------------------|
| Scheme 1 & Scheme 2  | 3.84 | 0.97     | 0.32             |
| Scheme 1 & Scheme 3  | 7.37 | 2.62     | 2.19             |
| Scheme 1 & Scheme 4  | 7.82 | 3.38     | 2.71             |
| Scheme 2 & Scheme 3  | 3.53 | 1.65     | 2.51             |
| Scheme 2 & Scheme 4  | 3.99 | 2.41     | 3.03             |
| Scheme 3 & Scheme 4  | 0.45 | 0.76     | 0.52             |
Results with second audio file

With the second audio file at a rate of $\frac{1}{2}$, it was noted that Scheme 4 surpasses Scheme 1 by at least 66 dB for all three transforms. Replacing FFT with DWT increases the gain of the system by 31 dB. At a rate of $\frac{2}{3}$, a gain of at least 75 dB on average is obtained by Scheme 4 over Scheme 1 for all three transforms. It is noted that using DWT with the schemes outperform the schemes using FFT by an average of 1 dB. With a rate of $\frac{3}{4}$, the highest gain is achieved with Scheme 4 which provides an average gain of over 69 dB over Scheme 1 with all three transforms. It is observed that the use of DWT increases the system gain by at least 34 dB when compared to FFT.

Table 21. Average gain in dB in each transform.

| Schemes          | FFT  | DWT Haar | DWT Biorthogonal |
|------------------|------|----------|------------------|
| Scheme 1 & Scheme 2 | 6.28 | 4.52     | 6.02             |
| Scheme 1 & Scheme 3 | 68.04| 45.60    | 47.91            |
| Scheme 1 & Scheme 4 | 71.28| 48.34    | 51.18            |
| Scheme 2 & Scheme 3 | 61.75| 41.08    | 41.89            |
| Scheme 2 & Scheme 4 | 65.00| 43.82    | 45.16            |
| Scheme 3 & Scheme 4 | 3.24 | 2.73     | 3.27             |
For both 16-QAM and 64-QAM, the gain of Scheme 2 over Scheme 1 is due to the prioritization of the control information bits in the prioritized constellation. The system is further enhanced by increasing the spacing between the constellation points in SQAM used in the Hybrid schemes. The gain obtained from Scheme 4 is higher than that of Scheme 3 as in Table 22.

Table 22. Average gain in dB between FFT and DWT transforms.

|             | DWT Haar |                      | DWT Biorthogonal |                      |
|-------------|----------|----------------------|------------------|----------------------|
| FFT         | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
| Scheme 1    | 59.23    | –        | –       | –       | 56.44    | –        | –       | –       |
| Scheme 2    | –        | 57.46    | –       | –       | –        | 56.17    | –       | –       |
| Scheme 3    | –        | –        | 36.79   | –       | –        | –        | 36.30   | –       |
| Scheme 4    | –        | –        | –       | 36.29   | –        | –        | –       | 36.33   |

Figure 13. Graph of SSNR against $E_b/N_0$ at rate 2/3.

Table 23. Average gain in dB in each transform.

| Schemes                  | FFT  | DWT Haar | DWT Biorthogonal |
|--------------------------|------|----------|------------------|
| Scheme 1 & Scheme 2      | 4.50 | 5.19     | 3.29             |
| Scheme 1 & Scheme 3      | 76.46| 70.70    | 69.90            |
| Scheme 1 & Scheme 4      | 79.29| 73.54    | 72.95            |
| Scheme 2 & Scheme 3      | 71.96| 65.51    | 66.61            |
| Scheme 2 & Scheme 4      | 74.79| 68.35    | 69.66            |
| Scheme 3 & Scheme 4      | 2.83 | 2.84     | 3.05             |

For both 16-QAM and 64-QAM, the gain of Scheme 2 over Scheme 1 is due to the prioritization of the control information bits in the prioritized constellation. The system is further enhanced by increasing the spacing between the constellation points in SQAM used in the Hybrid schemes. The gain obtained from Scheme 4 is higher than that of Scheme 3 as in Table 24.

Table 24. Average gain in dB between FFT and DWT transforms.

|             | DWT Haar |                      | DWT Biorthogonal |                      |
|-------------|----------|----------------------|------------------|----------------------|
| FFT         | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
| Scheme 1    | 46.27    | –        | –       | –       | 46.89    | –        | –       | –       |
| Scheme 2    | –        | 46.96    | –       | –       | –        | 45.68    | –       | –       |
| Scheme 3    | –        | –        | 40.51   | –       | –        | –        | 43.32   | –       |
| Scheme 4    | –        | –        | –       | 40.53   | –        | –        | –       | 40.55   |
Scheme 3, SQAM is applied only to the systematic bits while for Scheme 4, SQAM is applied to systematic as well as parity bits. The use of DWT gives a high boost in the system when compared to FFT. Same trend is observed in LTE and Wi-Fi.

**Complexity analysis of implemented system**

A detailed complexity analysis for each implemented scheme is given in Table 27. As can be noted from the table, various code blocks, which were not used in the conventional one, were added to implement the new system. Each of the added coding block performs a specific task which helps to enhance the conventional system.
This paper proposed three UEP schemes for the transmission of MP3 over LTE and Wi-Fi. The first scheme used the unequal importance of the MP3 bits and a prioritized QAM constellation mapping to provide more protection to the high importance bits. The second and third schemes used the statistical distribution of source symbols to map the systematic bits of the encoded symbols to the QAM constellation. In the second scheme, only the systematic bits were mapped onto the SQAM constellation while the parity bits were mapped onto the conventional QAM constellation. For the third scheme, both the systematic and parity bits are mapped onto the SQAM constellation. The schemes gave an average gain of 1–20 dB to the overall system. These gains come at the cost of an increase in complexity at the transmitter and receiver, as detailed in Table 27. However, given the gains obtained, the additional complexity cost is outweighed and the proposed schemes appear very promising for audio transmission over wireless channels. The gains from the new schemes can prevent interruptions to an audio stream and stop gaps in an audio stream for periods of time easily perceptible by the human ear. The use of DWT increased the system performance up to 90 dB with 16 QAM at rate 1/2. The reason is that the wavelets for DWT are located in both time and frequency domain while the sinusoids of FFT are localized in the frequency domain only. Also, the sinusoids of FFT are smooth and regular while the wavelets of DWT can be sharp or smooth and regular or irregular. FFT can only provide details about the different frequency components present in a signal and their respective amplitudes. DWT provide the same details as FFT as well as frequency components position on the time axis. DWT eliminates the use of cyclic prefix thereby maximizing the bandwidth requirement while minimizing the bit error rate of the system.

**Disclosure statement**

No potential conflict of interest was reported by the authors.
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