
Jin Ren

1. School of Electronic and Information Engineering, North China University of Technology, No.5 Jinyuanzhuang Road, Shijingshan District, Beijing, P.R, China

Abstract: The advance of wireless communications brings in various schemes of wireless digital communication technology. Analog communication and broadcasting services convert into digital services in many countries. This paper develops simulation models to characterize the bit error rate (BER) performance of HDR (HD-Radio), digital audio broadcasting (DAB), DAB+, terrestrial digital multimedia broadcasting (T-DMB) affected by Doppler spread. The IBOC (In-Band On-Channel) system has been developed to work in the same band with the conventional analog radio and broadcasting digital signal simultaneously. HDR (HD-Radio) standard of IBOC (In-Band-On-Channel) can use coherent demodulation using pilot sub-carriers. But DAB, DAB+ and T-DMB standard of Eureka-147 uses non-coherent demodulation by differential modulation. Theoretically, coherent demodulation is better than non-coherent demodulation. To contribute to decision of digital radio standard and design of digital radio transmission network, the simulation results will give a help.

Keywords: Digital audio broadcasting; DAB+; T-DMB; HD Radio; IBOC

1. Introduction

Digital radio broadcasting systems have come into the spotlight recently worldwide. Many digital radio broadcasting standards have been proposed recently, and the adoption of digital broadcasting is considered in many countries. But choosing most proper digital radio standard has become an important question for the successful deployment of the new radio service [1-2]. In addition, to decide the national standard of digital radio broadcasting service, various considerations are required like economic efficiency, social influence, and technical suitability, etc.

HD Radio is the trademark for iBiquity Digital Corporations in-band on-band (IBOC) digital radio system. While there are differences between amplitude modulation (AM) and frequency modulation (FM) band HD Radio systems, an HD Radio signal can be generally described as a digitally modulated RF signal that is transmitted around, under and alongside the present-day analog AM and FM signals. It should be noted that, strictly speaking, a hybrid HD Radio signal actually has components - an analog modulated component referred to here [3-4]. There digital signals are composed of multiple orthogonal frequency division multiplexed (OFDM) subcarriers, which are transmitted at a level to meet the specifications of the RF masks (AM and FM) as mandated in the United States by the Federal Communications Commission (FCC), and specified in the digital radio broadcasting standard (NRSC-5-A) of the National Radio Systems Committee (NRSC). Since the OFDM subcarriers of the HD Radio signals are contained with these masks, and are therefore considered to be contained within the allotted channel for a given station without allocating any additional spectrum, it is considered to be an in-band on-channel system. The FM HD Radio signal has more spectrum space available than the AM HD Radio signal, as the FM channel has been allocated greater bandwidth. Therefore, the FM HD Radio signal can operate at a higher data rate than AM HD Radio signal. This greater data rate can be subdivided to allow additional audio channels to be transmitted on the frequency.

The digital audio broadcasting (DAB) has recently become popular around the world, due to its ability to provide high quality reception additional features compared to the traditional AM/FM radio. It was developed in the 1990s by the Eureka 147/DAB project. In the meantime, the World DAB Forum have developed an upgrade of the Eureka 147 DAB system called DAB+ in order to improve the audio coding efficiency using the new coding schemes of MPEG-4HE AAC v2. Digital multimedia broadcasting (DMB) is one of the applications which have emerged from Eureka-147 DAB system. Particularly in Korea, DMB focuses on the broadcasting of moving pictures and their reception in harsh conditions such as in places surrounded by high buildings and on highways where vehicles are moving at a very high speed. There are two kinds of DMB systems, satellite DMB and terrestrial DMB. The terrestrial DMB is called by T-DMB in Korea [5-6]. Although the T-DMB system is an improved version of the DAB system, should still be used in many parts of the T-DMB system.

The described sections of this paper are as follows: Section 2 introduces HDR standard, Section 3 is about DAB, DAB+, and T-DMB. COFDM and Channel Model in Doppler Scenarios will be introduced in Section 4 and Section 5 respectively. In Section 6 implementation results of simulation will be reported.

2. HD radio

A logical channel is a signal path that conducts Layer 2 PDUs (Protocol Data Unit) in transfer frames into Layer 1 with a specific grade of service, determined by service mode. Lay 1 of the FM air interface provide 11 logical channels to higher layer protocols [7]. Not all logical channels are used in every service mode. There are five primary logical channels that can be used with the Hybrid, Extended Hybrid, and All Digital waveforms. They are denoted as P1, P2, P3, P4, and PIDS. The PIDS channel transmits the Station Information Service (SIS) information. There are six secondary logical channels that are used only with the All-Digital waveform. They are denoted as S1, S2, S3, S4, S5, and SIDS. The bits in each logical channel are scrambled to randomize the time-domain data. The inputs to the scramblers are the active logical channels as selected by the service mode. Channel encoding improves system performance by increasing the robustness of the signal in the presence of channel impairments. This function uses convolutional encoding. The size of the logical channel vectors is increased in inverse proportion to the code rate. The encoding techniques are configurable by service mode. Diversity delay is also imposed on selected logical channels. At the output of the channel encoder, the logical channel vectors retain their identity. The interleaving techniques are tailored to very high frequency fading environment and are configurable by service mode. In this process, the logical channels lose their identity. The interleaver output is structured in a matrix format, each matrix consists of one or more logical channels and is associated with a particular portion of the transmitted spectrum. OFDM subcarrier mapping assigns interleaver partitions to frequency partitions. One row of each active interleaver matrix is processed every OFDM symbol to produce one output vector which is a frequency-domain representation of the signal.

3. DAB, DAB+, T-DMB

The source encoder for the DAB system is the MPEG Audio Layer II encoder with restrictions on some parameters and some additional protection against transmission errors. The MPEG II audio signal and the other data are the input services to DAB transmitter. Each service signal is coded individually at source level in the transmitter, error protected, and then time interleaved in the channel coder. Each service is independently error protected with a coding overhead ranging from about 25% to 300%, the amount of which depends on the
The sub-carrier spacing is set to be is ICI (inter-carrier interference) caused by the time-varying nature of the channel given as  

\[ f_{\text{sub}} = \frac{f_{\text{c}}}{N} \]  

We obtain  

\[ n_{\text{start}} = \frac{T}{f_{\text{sub}}} \]  

The OFDM symbol is  

\[ s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} a_k e^{j2\pi nk/N} \]  

The samples  

\[ s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} a_k e^{j2\pi nk/N} \]  

are transmitted through the channel model. We indicate with  

\[ h(n) = h(n-T) \delta(n-T) \]  

The index  

\[ i = -\infty, \ldots, +\infty \]  

de the delay variable so that the delay variable so the equivalent discrete time channel impulse response reads as  

\[ h(qT, iT) = \sum_{i=1}^{T} h_i(qT) \delta(iT - iT) \]  

The samples  

\[ s(qT) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} a_k e^{j2\pi nk/N} \]  

are obtained via the convolution of the transmit samples with  

\[ y(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} s(k) e^{j2\pi kl/N} = n(qT) \]  

We then substitute (1) into (3) to write  

\[ y(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} s(k) e^{j2\pi kl/N} + n(qT) \]  

which upon defining the time-varying channel transfer function  

\[ h(k, qT) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} s(k) e^{j2\pi kl/N} + n(qT) \]  

The FFT output at the  

\[ k^{th} \]  

subcarrier can be expressed as  

\[ y(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} y(l) e^{j2\pi kl/N} \]  

where  

\[ h(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} h(l, qT) \]  

is ICI (inter-carrier interference) caused by the time-varying nature of the channel as given as  

\[ I(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} s(l) \sum_{q=0}^{T} H(i, qT) e^{j2\pi ikl/N} \]
and \( N(k) \) denotes discrete Fourier transform of the white Gaussian noise \( n(qT) \)

\[
N(k) = \frac{1}{\sqrt{N}} \sum_{q=0}^{N-1} n(qT) e^{-j2\pi qk/N}
\]

(9)

The received signal after excluding the guard interval can be expressed in vector form as

\[
y = Hs + n \tag{10}
\]

where \( y = [y(0), y(1), \ldots, y(N-1)]^T \), \( s = [s(0), s(1), \ldots, s(N-1)]^T \), \( n = [n(0), n(1), \ldots, n(N-1)]^T \), and the time-varying channel matrix \( H \) is given by where the first and second indices of \( H(.,.) \) in (11) represent the discrete time and frequency variables, respectively.

\[
H = \begin{bmatrix}
H(0,0) & H(1,0) & \cdots & H(N-1,0) \\
H(0,1) & e^{j2\pi/N}H(1,1) & \cdots & H(N-1,1)e^{j2\pi(N-1)/N} \\
\vdots & \vdots & \ddots & \vdots \\
H(0,N-1) & e^{j2\pi(N-1)/N} & \cdots & H(N-1,N-1)e^{j2\pi(N-1)(N-1)/N}
\end{bmatrix}
\tag{11}
\]

5. Channel model in Doppler scenarios

In wireless communication, \( h(t, \tau) \) is always modeled as a wide sense stationary uncorrelated scattering (WSSUS) process with \( L+1 \) received path, such that

\[
h(t, \tau) = \sum_{l=0}^{L} h_l(t) \delta(\tau - \tau_l)
\tag{12}
\]

where \( t \) and \( \tau \) are time and delay respectively, \( h_l(t) \) is the \( l \)th path gain and its power density spectrum \( P_l(f) \). The variance \( \sigma^2 \) determines the average speed of variation in time, i.e. describes the influence of the Doppler effect on the waves arriving at delay time \( \tau_l \).

Therefore \( P_l(f) \) is also known as Doppler spectrum.

A basic parameter is the maximum Doppler frequency

\[
f_d = \frac{V}{\lambda}
\tag{13}
\]

where \( V \) is the velocity of the receiver or surrounding objects and \( \lambda \) is the wavelength of the transmitted signal.

In case that all waves are arriving from all directions at the receiving antenna with approximately the same power the real Doppler spectrum can be approximated by

\[
P_d(f) = \frac{\lambda}{\sqrt{\left(f/f_d\right)^2 - 1}} \text{ for } f \in [-f_d, f_d]
\tag{14}
\]

This spectrum is also known as “classical ‘Jakes’ spectrum”. It will be denoted “Classical” in Table 2.

6. Simulation Results

Table 1 is OFDM system standard parameter previous system. Simulation environment of the systems in this paper is used general multipath fading channel, given by Table 2. Follwing, Fig 1 (a), Fig 2 (a) and Fig 3 (a) show BER performances for HDR-MP3, and Fig 1(b), Fig 2(b) and Fig 3(b) show BER performances for DAB, DAB+, and T-DMB respectively in multipath fading channel, i.e, TAB-2, TAB-3 and TAB-7. When velocity is 60km/h, 150km/h and 300km/h, so doppler shift frequency is 5.5Hz, 13.9Hz and 27.8Hz respectively. In Fig 1 (a), Fig 2 (a) and Fig 3 (a), the performance of P1 is better than P3, because the code rate of P1 is lower than P3. The code rate of P1 is 2/5, and P3 is 1/2. Interleaving depth of \( \text{P3} \) is longer than \( \text{P1} \), and if velocity is increased, the gap is expected to be decreased since \( \text{P3} \) may obtain more diversity gain.

### Table 1. System Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>HDR(MP3)</th>
<th>DAB</th>
<th>DAB+</th>
<th>T-DMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guard Interval (us)</td>
<td>100</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>( T_{FFT} ) (ms)</td>
<td>2.8</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(OFDM) Sym. duration (ms)</td>
<td>2.9</td>
<td>1.25</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>FFT size (N)</td>
<td>4096</td>
<td>2048</td>
<td>2048</td>
<td>2048</td>
</tr>
<tr>
<td># of Useful sub-carriers</td>
<td>458</td>
<td>1536</td>
<td>1536</td>
<td>1536</td>
</tr>
<tr>
<td>% of Pilot sub-carriers</td>
<td>5.68</td>
<td>1.32</td>
<td>1.32</td>
<td>1.32</td>
</tr>
<tr>
<td>Path no.</td>
<td>TAB-2 (Classical)</td>
<td>Delay (μs)</td>
<td>Doppler (Hz)</td>
<td>Att (dB)</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------</td>
<td>------------</td>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
<td>5.2314</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>5.2314</td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>5.2314</td>
<td>3.0</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>5.2314</td>
<td>4.0</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>1.2</td>
<td>5.2314</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>6</td>
<td>1.4</td>
<td>5.2314</td>
<td>0.0</td>
<td>1.9</td>
</tr>
<tr>
<td>7</td>
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<td>5.2314</td>
<td>3.0</td>
<td>2.1</td>
</tr>
<tr>
<td>8</td>
<td>2.4</td>
<td>5.2314</td>
<td>5.0</td>
<td>2.5</td>
</tr>
<tr>
<td>9</td>
<td>3.0</td>
<td>5.2314</td>
<td>10.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

In Fig. 1 (a), performance of P1 is better than P3. P1 is 6.4dB, and P3 is 8.2dB by $10^{-4}$ BER. Also P1 is 8.4dB and P3 is 10.3dB by $10^{-6}$ BER. In Fig 2 (a), performance of P1 is better than P3. P1 is 5.2dB, and P3 is 6.7dB by $10^{-5}$ BER. Also P1 is 8.3dB and P3 is 9.2dB by $10^{-4}$ BER. In Fig 3 (a), performance of P1 is better than P3. P1 is 7.2dB, and P3 is 7.5dB by $10^{-4}$ BER. Also P1 is 8.2dB and P3 is 8.4dB by $10^{-6}$ BER. The reason of P1 better than P3 is each other code rate. Code rate of P1 is 2/5, and P3 is 1/2. So P1 is excellent for error correction performance. Interleaving depth of P3 (2 frame) is longer than P1 (1 frame). So if velocity increases, differences in performance decrease by time diversity.

In Fig 1(b), the performance of T-DMB is best and DAB+ is better than DAB. T-DMB is 12.2dB, DAB+ is 12.8dB and DAB is 13.8dB by $10^{-3}$ BER. Also T-DMB is 13.2dB, DAB+ is 14.3dB and DAB is 20dB T-DMB by $10^{-4}$ BER. In Fig. 2(b), the performance of T-DMB is best and DAB+ is better than DAB. T-DMB is 11.8dB, DAB+ is 12.9dB and DAB is 14dB by $10^{-3}$ BER. Also T-DMB is 13dB, DAB+ is 14.2dB and DAB is 20dB T-DMB by $10^{-4}$ BER. In Fig. 3(b), the performance of T-DMB is best and DAB+ is better than DAB. T-DMB is 14dB, DAB+ is 15.1dB and DAB is 18dB by $10^{-3}$ BER.

From all Figures, the performances of HDR-MP3 is better than DAB, DAB+ and TDMB in different Doppler scenarios.

Figure 1. (a) BER performance of HDR-MP3 for Ch. TAB-2

<table>
<thead>
<tr>
<th>Sampling rate (Msps)</th>
<th>1.488</th>
<th>2.048</th>
<th>2.048</th>
<th>2.048</th>
</tr>
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<tbody>
<tr>
<td>Sub-carrier spacing (Hz)</td>
<td>363.37</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Occupying BW (kHz)</td>
<td>167</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Data symbol rate (ksps)</td>
<td>149</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Data rate (kbps)</td>
<td>124</td>
<td>1200</td>
<td>1100</td>
<td>1106</td>
</tr>
<tr>
<td>Spectral Efficiency</td>
<td>0.74</td>
<td>0.8</td>
<td>0.73</td>
<td>0.74</td>
</tr>
</tbody>
</table>
7. Conclusion
In this paper, we evaluate performances of digital radio technologies (HDR versus DAB, DAB+, and T-DMB). Technically, HDR standard uses coherent demodulation by pilot sub-carrier. DAB, DAB+ and T-DMB standard of Eureka-147 uses non-coherent demodulation by differential modulation. From the simulation results, it can be clearly seen that different system performances under various Doppler scenarios. The performance of HDR is better than DAB, DAB+ and T-DMB. The reference data of simulation will be useful for experimental broadcasting.

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