Interleaving IBOC Signals for a Digital HD Radio Multiplex

Philipp Schmid
Nautel Ltd
Hacketts Cove, NS, Canada
pschmid@nautel.com

***Abstract*—With increased saturation of the VHF band II used for FM, few frequencies are available for new radio stations in many markets. This paper describes the benefits of using the In Band On Channel (IBOC) signal in an all-digital configuration to boost the number of effective audio services in the FM band. A new method of creating an all-digital IBOC signal configuration is described. Multiple instances of the dual sideband IBOC signal are frequency shifted and added to create a multiplex of independent IBOC signals. This multiplex can then be broadcast using a single wide-band IBOC capable broadcast transmitter and antenna system with or without an FM carrier. In order to maintain a practical amplifier Peak-to-Average Power Ratio (PAPR) the multiplex must be processed by a modified PAPR reduction algorithm that factors in the frequency shift of the individual IBOC signals. Among other combinations, it is possible to combine 3 IBOC stations with an occupied bandwidth of 600 kHz and receive up to 15 audio services on HD Radio receivers available today.**

This paper proposes to retain VHF band II for its intended purpose of sound broadcasting and consider the possibilities of an extended FM band including TV channel 5 and 6. A build out of the FM band maintaining existing FM services, embracing hybrid FM plus IBOC stations and introducing all digital IBOC broadcasts promises to provide a smooth digital radio transition with the end goal of improved spectral efficiency and lower transmission costs.

***Index Terms*—FM, IBOC, HD Radio, spectral efficiency, spectral planning, OFDM, QPSK, PAPR, crest factor reduction, frequency reuse, HD Multiplex, advanced RF modulation**

I. Introduction

There is much debate in the broadcast industry and regulatory bodies on the future of the FM band II. It is clear that globally this limited resource is becoming increasingly sparse especially in urban centers with many markets providing an effective audio offering of no more than 25 to 30 FM stations on the typical radio dial. Listeners today demand a greater diversity of audio content as proliferated by today's on-demand multimedia culture. Also many national broadcasters want to benefit from lower energy costs of digital radio. This leads many countries to consider alternatives to traditional FM broadcasting, such as Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), and others in band III located between 174 MHz and 240 MHz. Norway is leading the way with official statements calling for the cessation of national FM broadcasting in 2017 [1], other countries, such as Denmark [1] and the United Kingdom [2] are closely monitoring digital listening and are prepared to make similar statements once 50% of listening is on a digital platform.

HD Radio[1] is a digital radio standard in use in the United States, Mexico, Canada, Panama, and the Philippines [3] providing an in band digital radio solution. In its present definition, the digital signal is added on-channel on both sides of the FM carrier. The signal is hence termed In Band On Channel (IBOC). At present there are over 2000 stations broadcasting this signal with over 1700 added audio services in multicast side-channels available only on HD Radio receivers [3] typically referenced as HD1 to HD5 on a receiver.

In this paper it is shown that the full potential of IBOC cannot be realized while operating in a hybrid FM+IBOC environment. A new all digital signal definition based on and compatible with the presently NRSC [4] defined IBOC standard is proposed. The new signal frequency shifts and adds multiple IBOC sidebands such as to make optimal spectrum use creating what is termed a digital HD multiplex in this paper.

Parallels can be drawn to the digital multiplex offered by DAB that shifts broadcasting from a single purpose transmission to a shared use channel multiplex. DAB promises lower transmission costs at 10x better energy efficiency compared to broadcasting 15 individual FM stations [5] and coverage can be matched to population centers using Single Frequency Networks (SFNs). This paper shows that these benefits can be made available to IBOC, as well, offering cost savings and added audio services. A single transmitter and antenna system is used to transmit HD multiplex with 15 or more audio services.

Unlike DAB, the proposed concept uses today's tri-mode receiver sets for all signal types: FM, FM+IBOC, and HD multiplex. All of these signals may co-exist across the FM band. It is not expected that legacy FM receivers will be obsoleted for some time. Furthermore, band II is maintained for its original purpose of sound broadcasting, which it has to maintain until FM is abandoned internationally and cross-border frequency allocations no longer have to be considered.

It has already been shown that matching IBOC coverage with comparable FM coverage is possible using a hybrid transmitter at about 10% IBOC signal power compared to

[1] HD Radio™ is a proprietary trademark of iBiquity Digital Corporation. The author is not affiliated with and this text is not endorsed by iBiquity.

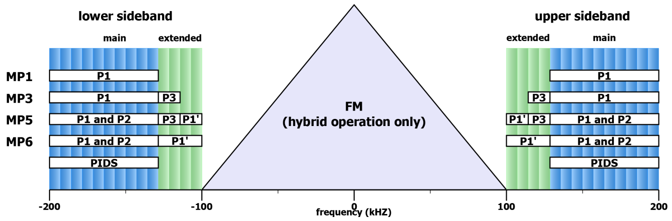

Fig. 1. IBOC spectral representation showing the location of logical channels P1, P2, P3, and the Primary IBOC Data Service (PIDS) within the IBOC carriers. P1' contains additional forward error correction (FEC) for all digital modes. The FM carrier is only present in hybrid operation.

Service Mode	Type	Data Rate (kbps) / Relative Robustness						Total kbps
		P1		P2		P3		
MP1	hybrid	98.4	2					98.4
MP3	hybrid	98.4	2			24.8	4	123.2
MP11	hybrid	98.4	2			49.6	4	148.0
MP5	digital	24.8	1	73.6	2	24.8	4	123.2
MP6	digital	49.6	1	48.8	2			98.4

TABLE I: IBOC Service Mode Data Capacities [9]

the FM [6]. HD multiplex is also expected to achieve FM comparable coverage. While DAB requires less field strength compared to FM for good reception [7] [8], band III suffers from additional signal propagation losses. DAB often has to resort to fielding multiple SFN nodes to achieve comparable coverage to the FM simulcast on DAB [8].

This poses the question: Can we supplement rather than replace band II with an all digital sound broadcasting solution?

The proposed HD Radio multiplex provides a practical method of achieving an all digital transmission with improved spectral efficiency and lower transmission costs. Much of today's broadcast infrastructure can be maintained with this approach. It is based on the hybrid FM HD Radio standard that can already be received on standard HD Radio receivers deployed today. Leveraging this installed receiver base and the wide availability of commercial HD Radio receivers promises to accelerate the digital transition period.

II. IBOC Signal

HD Radio^{TM} uses the IBOC signal specification [4] originally developed by USA Digital Radio that later formed iBiquity Digital Corporation. IBOC was initially introduced as a hybrid signal that maintains the traditional FM carrier while simulcasting the FM audio content on digital carriers and offering additional multicast audio and data services to HD Radio receivers only. This approach allows for a transition period supporting legacy FM receivers until enough digital radio receivers have been fielded to warrant all digital IBOC transmission. Over 25 million HD Radio receivers are in use today with many available receiver models and over 200 automobile models offering HD Radio receivers [3].

The hybrid FM plus IBOC signal places two sidebands of Orthogonal Frequency Division Multiplex (OFDM) carriers on either side of an FM carrier as shown in figure 1. Each sideband is organized into a number of frequency partitions each composed of 18 data bearing carriers and flanked by reference carriers on either side. The system can be configured for several possible service modes that enable different combinations of frequency partitions and Forward Error Correction (FEC) robustness. In the basic MP1 service mode, 10 frequency partitions are enabled per sideband for a total of 382 carriers across both sidebands; note the additional reference carrier on the outside of either sideband.

The ratio between the total integrated power of all 382 IBOC carriers to the single FM carrier is termed the IBOC injection ratio. Typically the injection is in the range of -20 dBc or 1% to -10 dBc or 10% of the FM carrier power. A detailed study conducted by National Public Radio (NPR) labs [6] of 50 example stations revealed that at an injection ratio of -10 dBc mobile reception of IBOC exceeds that of FM reception at 117% of population served compared to good analog FM reception. Indoor and portable reception of IBOC is slightly reduced at 83% and 81% of analog FM coverage respectively. This demonstrated the point that a band II digital solution can achieve FM coverage parity.

It is on the basis of these findings that this paper uses the approximation that the coverage of an all digital IBOC transmitter at 10% of analog FM power levels roughly equates to FM coverage. This is an approximation as the coding gain and total power requirements of all digital service modes as discussed in section IV-B need to be factored in for a complete analysis.

Advanced service modes, such as service mode MP3, enable 2 additional frequency partitions in toward the FM carrier. When enabling up to 4 additional frequency partitions as per service mode MP11, the IBOC signal occupies a full 100 kHz on either side of the FM carrier. This typically requires reducing or carefully controlling FM modulation in order to avoid the FM spectral content from bleeding into the IBOC carriers. Table I provides an overview of common service modes and their associated data capacities.

The total capacity is broken into logical channels, referred to as P1, P2, and P3. Each logical channel has varying degrees of forward error correction associated with it designated with a relative robustness number, where 1 represents the highest robustness. The coding gain for some of these service modes is discussed further in section IV-B. The total data capacity is a function of the total number of enabled quadrature phase shift keyed (QPSK) modulated carriers less the amount used by forward error correction.

A. *Peak-to-Average-Power Ratio Reduction*

The FM signal is a single continuous wave carrier system with a constant base band envelope. IBOC, on the other hand, is the summation of a multitude of OFDM carriers that together create an almost noise like base band envelope. Therefore, in order to maintain a reasonable PAPR suitable for broadcast transmitters a PAPR reduction algorithm is used

[10]. The essence of this algorithm introduces noise within the frequency domain IBOC constellation such as to cancel peaks in the time domain. This is possible since the Quadrature Phase Shift Keying (QPSK) nature of IBOC is insensitive to noise and can tolerate a degree of distortion without affecting signal reception. The basic steps of this algorithm are

1) The signal is clipped in the time domain limiting the absolute peak while maintaining the base band phase in the IQ domain.
2) The time domain signal is converted into the frequency domain using a Fast Fourier Transform (FFT) after removing the pulse shaping function.
3) Frequency bins outside of the signal bandwidth are reduced.
4) The in-band constellation points are cleaned to avoid excessive noise.
5) The result is transferred into the time domain using an inverse FFT process.
6) These steps are repeated until a reasonable PAPR is achieved.

The gains of the time domain clipping are partially undone in the frequency domain correction steps. An iterative approach eventually settles the PAPR from over 12 dB to around 6-8 dB (see table II). In a hybrid signal configuration taking the added FM carrier into account leads to significant saving in the combined PAPR [10]. When creating an all digital signal configuration by interleaving IBOC signals this algorithm must be modified as described in section III.

B. All Digital Signal

There are two types of service modes: hybrid and all digital service modes as indicated in table I. Hybrid service modes expect the FM carrier to be present and force an HD Radio receiver to play the FM audio prior to blending to the digital simulcast. Digital service modes, on the other hand, mute the HD Radio receiver initially to squelch the non-existent FM audio prior to producing the digital audio stream. Since all digital service modes have no analog fall back audio, digital service modes generally make a higher robustness logical channel available for the main audio transmission (see section IV-B) and possible other audio streams.

The challenge with the all digital service modes MP5 and MP6 is that once the FM carrier is turned off 200 kHz of bandwidth are left unoccupied. The IBOC standard [4] provides a definition of secondary service mode carriers (MS modes) that fill in the 200 kHz of the FM carrier at a configurable power level below the main outer carriers. This signal configuration promises enhanced data capacity and more audio streams. While this signal configuration is of interest and can also be applied to the interleaved IBOC signal configuration, at the time of writing secondary service modes have not yet been implemented on the broadcast side and consequently receivers are lacking support for these modes as well. Hence there is no value proposition for turning off the FM carrier in favor of secondary service modes at this time.

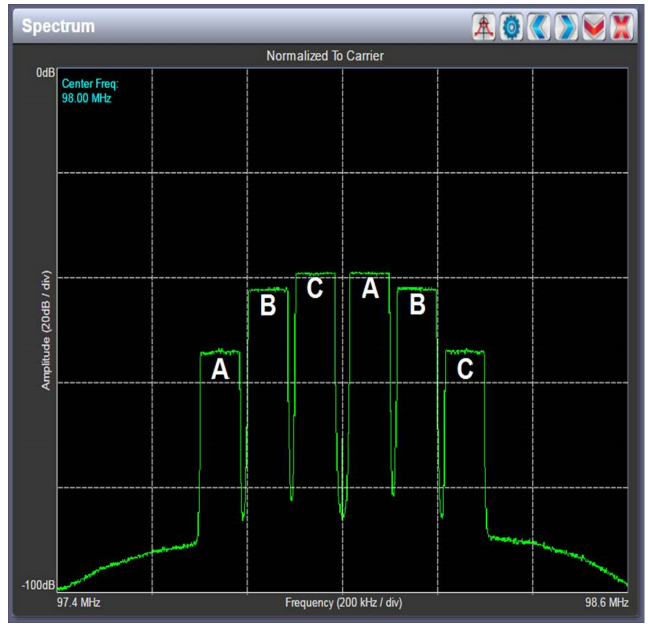

Fig. 2. Spectrum of HD multiplex in MP3 mode captured from a single IBOC transmitter broadcasting three stations A, B and C at 97.9 MHz, 98.0 MHz and 98.1 MHz. Each station may carry up to 5 audio services.

III. Interleaving IBOC Signals

The concept presented in this paper explores how we can define an all digital IBOC signal standard that makes use of the existing base of IBOC receivers in common use today. We can fill the 200 kHz void left by the FM carrier with additional sets of OFDM carriers that are independently modulated. By frequency shifting and interleaving these sets of IBOC carriers we can create a multiplex of HD radio signals, later simply termed HD multiplex, of varying occupied bandwidths and payload capacities. The addition of these signals can be broadcast from a single transmitter and antenna system making use of a larger and more efficient transmitter.

Figure 2 shows an example signal configuration of three sets of IBOC carriers marked as sets A, B and C. In this example, service mode MP3 was chosen, as it does not utilize the entire 100 kHz of bandwidth alloted to each sideband clearly outlining the IBOC sidebands. A similar configuration can be created using service mode MP5, which then fills in the remaining frequency gaps in between sidebands. This provides the signal with additional FEC as seen by the robustness numbers in table I. In this way the entire 600 kHz of occupied bandwidth are used.

The receiver will tune only into the sidebands of interest and ignore the remaining sets of carriers. For example, if the multiplex is centered at 98.0 MHz, a receiver would tune into station A at 97.9 MHz, station B at 98.0 MHz and station C at 98.1 MHz. All HD Radio receivers on the market today are capable of tuning into station A and C. Those receivers equipped with European tuning modes capable at dialing in 100 kHz frequency steps will receive the full multiplex. Once tuned to a station, the receiver can select the HD2 to HD5 sub channels. Please note that this is the most basic signal configuration further combinations are also possible as shown in figure 4.

The concept is based on the key observations in the following sections.

A. Frequency Shifted Peak Reduction

We cannot simply treat the carriers of a shifted station as added to the original OFDM signal. IBOC symbols are cyclic in nature, while the frequency shift is a continuous wave. Note that the receiver does not see this shift as it directly tunes to the channel frequency. It only needs to be considered when looking at a shifted station at the baseband In-phase and Quadrature (IQ) signal and bringing the carriers back into the frequency domain using the FFT this interaction with the continuous frequency shift causes a phase shift from one symbol to the next. To the standard PAPR reduction algorithm, this rotation appears incorrectly as noise to be corrected. Therefore, we must alter the standard algorithm to make it aware of which sets of carriers are shifted. First consider the definition of the n^{th} IBOC symbol as defined by NRSC-5C [11]:

$$y_n(t) = h(t - nT_s) \sum_{c=C_{min}}^{C_{max}} \bar{X_n}[c] e^{j2\pi\Delta fc(t-nT_s)} \quad (1)$$

where

- $n = 0, 1, 2, 3..., \infty$ and $0 \leq t < \infty$
- $\bar{X_n}[k]$ is the per carrier complex constellation value matrix defined here as corresponding to the carrier c.
- h(t) is the pulse-shaping function as defined in section 13.2 of NRSC-5C [11].
- T_s is the symbol duration of 2.9 ms and Δf is the carrier spacing of 363.4 Hz

In equation 1, the $(t - nT_s)$ term effectively resets the phase of each carrier from one symbol to the next as the complex carrier shift always starts at $e^0 = 1$ at the beginning of each symbol. Let's look at what happens when a continuous frequency shift is added to equation 1. In order to be able to use a single FFT process for PAPR reduction, the shift must be a multiple, m, of Δf such that the energy of each carrier falls nicely into a single frequency bin. For a 100 kHz carrier shift, m is chosen to be 275 resulting in an effective carrier shift of 99.928 kHz. At a carrier frequency of 87.5 MHz this results in a 0.82 ppm frequency error that is well within the 1 ppm specified limit [12]. Equation 2 applies this frequency shift to equation 1:

$$y_n(t) = e^{j2\pi m\Delta ft} h(t - nT_s) \sum_{c=C_{min}}^{C_{max}} \bar{X_n}[c] e^{j2\pi\Delta fc(t-nT_s)} \quad (2)$$

$$y_n(t) = h(t - nT_s) \sum_{c=C_{min}}^{C_{max}} \bar{X_n}[c] e^{j2\pi\Delta f(m+c)(t-\frac{cnT_s}{m+c})} \quad (3)$$

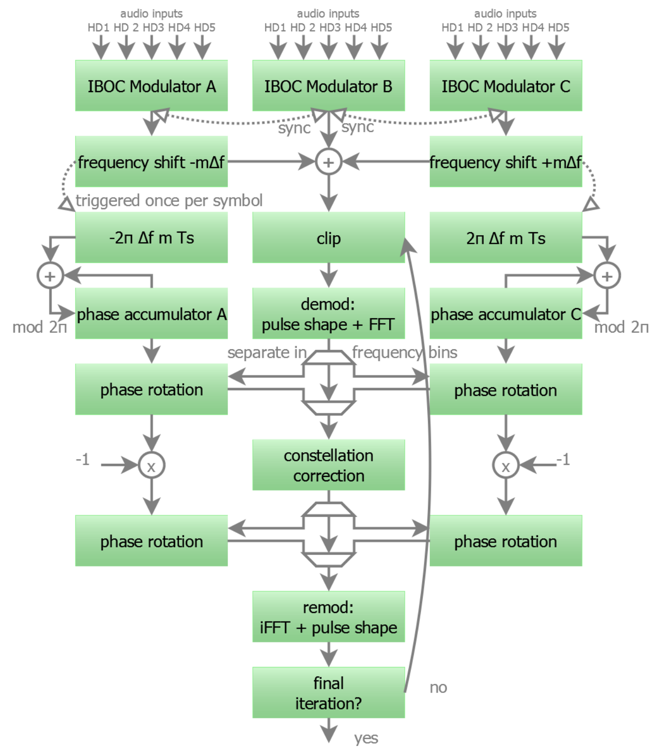

Fig. 3. Modified PAPR reduction algorithm taking into account the symbol-to-symbol phase rotation in frequency shifted IBOC modulator outputs.

In equation 3 we can see that carrier c is now shifted by a frequency of $(m + c)$. However, the $(t - \frac{cnT_s}{m+c})$ term now no longer evaluates to zero at discrete symbol intervals T_s leaving a residual changing phase from symbol to symbol. Evaluating equation 3 at $t = nT_s$ provides:

$$y_n(t = nT_s) = h(0) \sum_{c=C_{min}}^{C_{max}} \bar{X_n}[c] e^{j2\pi\Delta fmnT_s} \quad (4)$$

This means that each carrier receives an incremental phase shift of $(2\pi\Delta fmT_s \mod 2\pi)$ at the start of each symbol compared to the previous symbol. We can safely apply the modulus operation, since multiple rotations leave the carrier constellation at the same phase value. For a 100 kHz shift at $m = 275$ and using exact representations for Δf and T_s evaluates to:

$$2\pi\frac{1488375}{4096}275\frac{135}{128}\frac{4096}{1488375} \mod 2\pi = 0.245rad = 14.1^\circ \quad (5)$$

Recognizing this symbol-to-symbol phase shift, we can modify the PAPR reduction algorithm described in section II-A by adding one phase accumulator for each shifted IBOC station that is incremented on each symbol. For each iteration of the PAPR reduction algorithm, the current value of the phase accumulator is applied prior to constellation correction and re-applied thereafter as shown in figure 3.

The center column in figure 3 essentially represents the standard PAPR reduction algorithm while the outer columns are the new additions. The figure shows an example of 3 interleaved IBOC stations, but other combinations are possible, as well. Each shifted station must maintain a complex shifting frequency based on $m\Delta f$ and compute the associated phase increment as shown above. At the start of each symbol, the phase accumulator is incremented by this value and the same accumulator value is used across all iterations within this symbol. Once the signal is converted into the frequency domain, the frequency bins are rotated by the phase accumulator value. The output of the frequency domain corrections are again rotated by the inverse of the phase accumulator in order to restore the original constellation point. Note that the pulse shaping function is not affected by the frequency shift as it is a real multiplication of a cosine function.

Note that a receiver can make use of this phase shifting principle in order to decode a number of simultaneous IBOC transmission using a single baseband down conversion path. This would allow the receiver to aggregate the payloads of multiple IBOC stations. Note that the receiver only needs to have a single symbol tracking loop, since all stations are in sync with one another.

B. Additional OFDM Carriers

The addition of more OFDM carriers does not significantly alter the effectiveness of the described PAPR reduction algorithm. In our lab we practically found no difference in the power envelope between the basic service mode MP1 and service mode MP6 with 40% more OFDM carriers. Table II shows the Complementary Cumulative Distribution Function (CCDF) for MP1 and MP6 evaluated at probabilities of 10^{-3} to 10^{-6}. The signal is above the stated PAPR for the given probabilities which show little variation between MP1 and MP6 confirming this observation. For both cases the same implementation of the PAPR reduction algorithm have been used. To demonstrate that it is possible to achieve a similar PAPR, an example signal composed of 3 interleaved MP5 signals similar to the configuration shown in figure 2 with a total of 1512 carriers. However, these numbers were taken with a better implementation of the PAPR reduction algorithm yielding better results and cannot be compared directly. It does show that PAPRs better than single MP5/6 are possible.

Probability	Carriers	PAPR (dB)			
		10^{-3}	10^{-4}	10^{-5}	10^{-6}
MP1	382	6.36	6.79	6.98	7.14
MP6	508	6.35	6.75	6.99	7.04
MP5 Multiplex	1512	5.40	5.52	5.58	5.62
Shifted MP5	1512	10.1	10.7	11.0	11.2

TABLE II: CCDF Probabilities

For comparison purposes, table II also includes a column for shifted MP5 not using the described method simply adding shifted signals. Since the Root Mean Squared (RMS) powers of the signals add for the average power and peaks are due to the addition in voltage, the overall PAPR increases to 11.7 dB given the MP6 PAPR. A transmitter not using the described method can expect to produce only 40% Transmitter Power Output (TPO) of a transmitter using this method. A comparable PAPR to a single IBOC signal is only obtained using the method described in section III-A.

C. Signal Orthogonality

The key concept that allows OFDM systems to pack a multitude of independent carriers into a minimum of occupied signal bandwidth is that all carriers are on orthogonal basis functions that satisfy the property shown in equation 6 [13].

$$\int_0^T \psi_i^*(t)\psi_k(t)dt = K_i\delta_{ik} \tag{6}$$

where one function must be complex conjugated and the delta operator is defined as

$$\delta_{ik} = \begin{cases} 1 & \text{for } i = k \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

The receiver can project the signal onto the orthogonal basis and effectively reject the frequency contribution of neighboring carriers and can be packed tightly together.

In order for HD Multiplex to pack individual stations closely together this property must be satisfied across the output of multiple independent IBOC modulators that are then frequency shifted by m frequency bins. To demonstrate this property a single carrier, i, from equation 1 and a shifted carrier, k, from equation 3 are inserted into equation 6. Note that this analysis is done after the pulse shaping function $h(t - nT_s)$ has been accounted for and the guard interval has been collapsed back on to the front of each symbol. Removing the guard interval results in a shortened symbol duration of $\frac{128}{135}T_s$.

$$\begin{aligned} \int_{nT_s}^{nT_s+\frac{128}{135}T_s} & \bar{X}_n[i]e^{-j2\pi\Delta f i(t-nT_s)} \\ & * \bar{X}_n[k]e^{j2\pi\Delta f(m+k)(t-\frac{knT_s}{m+k})}dt \end{aligned} \tag{8}$$

Evaluating the integral:

$$= \frac{\bar{X}_n[i]\bar{X}_n[k]e^{j2\pi\Delta f n(1-k)T_s}}{j2\pi\Delta f(m+k-i)} e^{j2\pi\Delta f(m+k-i)t}\Big|_{nT_s}^{nT_s+\frac{128}{135}T_s} \tag{9a}$$

$$= \frac{K_i}{j2\pi\Delta f(m+k-i)}(e^{j2\pi\Delta f(m+k-i)\frac{128}{135}T_s)} - 1) \tag{9b}$$

Substituting exact values [11]:

$$\begin{aligned} & \frac{4096K_i}{1488375}\frac{e^{j2\pi\frac{1488375}{4096}(m+k-i)\frac{4096}{1488375}} - 1}{j2\pi(m+k-i)} \\ & \frac{4096K_i}{1488375}\frac{e^{j2\pi(m+k-i)} - 1}{j2\pi(m+k-i)} \end{aligned} \tag{10}$$

We can see from equation 10 that for any integer value of $m + k - i$ the expressions evaluates to zero satisfying the condition for $i \neq (m+k)$. To see if the $i = m+k$ case is also satisfied, we use Euler's formula to expand the numerator as shown in equation 11. For $i = m + k$ and $m, i, k \in \mathbb{Z}$:

$$\begin{aligned}
&\bar{K}_i \frac{cos(2\pi(m+k-i)) - 1 + jsin(2\pi(m+k-i))}{j2\pi(m+k-i)} \\
=&\bar{K}_i \frac{jsin(2\pi(m+k-i))}{j2\pi(m+k-i)} \\
=&\bar{K}_i sinc(2(m+k-i)) = \bar{K}_i
\end{aligned} \tag{11}$$

Since the $sinc(0)$ function assumes the value of 1, we have shown that that any arbitrary carrier i of an unshifted IBOC signal is orthogonal in all cases to any arbitrary carrier k that is shifted by an arbitrary frequency shift m provided m is an integer. Any reference to the symbol number is absorbed in the constant $\bar{K}_i$, which indicates that this property is true for all symbols not just the first. Maintaining orthogonality means shifted IBOC sidebands can be placed side-by-side with other IBOC sidebands originated from another modulator with any arbitrary shift provided the modulators are synchronized to provide symbols at the same time. This is shown in figure 3 by indicating that these modulators are synced to one another.

D. Interleaving IBOC Signals

The interleaving pattern shown in figure 2 is the most basic configuration. With an occupied bandwidth of 600 kHz, the resultant signal fits nicely into the lowest possible IBOC modulator sample rate. This base rate is derived from the highest carrier number in a single IBOC signal being 546 requiring at least 1092 frequency bins in the modulator. A length of 2048 is the next convenient 2^n FFT length and translates into 2048 samples in the time domain. A guard interval of 112 samples ($\alpha = \frac{7}{128}$) is added to these for a total of 2160 samples in a symbol. Leading to a base sample rate of $f_s = \frac{2160}{T_s} = 744187.5\ Hz$.

We are effectively utilizing only 508 carriers out of a possible 2048 in this configuration. Adding two IBOC signals shifted by $m = 275$ and $m = -275$ now utilizes carriers from -821 to +821 which still fits into our 2048 point FFT length. This means that the base sample rate can carry the HD multiplex and there is little computational impact to the PAPR reduction algorithm since FFT lengths are maintained.

Figure 4a shows the basic interleaving pattern with 600 kHz of occupied bandwidth that is also shown in figure 2. Please note that the levels of the individual sidebands are somewhat arbitrary and have been chosen in this example such as to help taper off the sideband shoulders due to possible transmitter non-linearity. To improve clarity, sidebands corresponding to the same station are marked in the same color and by the same letter code. A right pointing arrow indicates a lower sideband and a left pointing arrow indicates an upper sideband. The corresponding tuning frequency for the receiver is indicated in the box below the frequency axis.

It is possible to run the described PAPR reduction algorithm at multiples of the base sample rate. This makes it possible to further extend the interleaving patterns with more sidebands. The easiest extension may be to simply duplicate the 600 kHz mode for a 1.2 MHz solution at an FFT length of 4096 points at 1488375 Hz. It may be desirable to spread the available tuning frequencies evenly as depicted in figure 4b. In this example sidebands B and G are optional single sideband configurations without a corresponding sideband partner that may be enabled in the future. With 5 IBOC stations already, turning off these sidebands for now has acceptable impact to the spectral efficiency of the overall system. It is conceivable to build wider signal combinations increasing transmitter linearity requirements over a wider bandwidth. It may be necessary to employ channel filters in order to maintain spectral compliance and reduce spectral re-growth at the shoulders. Advanced AM-AM correction and memory effect compensation are a must for these signal types.

E. Single Sideband Modes

When turning off a sideband, the robustness of the single sidebands B and G in 4b is significantly compromised. At IBOC convolution code rates of 2/5 [11] turning off one sideband effectively punctures the overall code rate to 4/5 leaving little FEC. A clean signal is required for good reception, therefore, figure 4 shows the single sidebands B and G at elevated power levels and the most robust IBOC service modes (MP5 and MP6) are recommended for this application. Compared to the other sidebands, single sidebands B and G require 3 dB more gain to compensate for the loss of the other sideband plus possibly another 6-8 dB to overcome losses in coding gain and frequency diversity. Finding the required gain could be an interesting extension of this work.

Single sideband reception has already been demonstrated on existing receivers. HD Radio receivers with improved single sideband reception modes will also benefit from greater sensitivity in standard hybrid signal cases, where one sideband is impaired by a 1st adjacent interferer. Provided receivers account for the loss of a single sideband in symbol tracking, existing service mode definitions already present in receivers today could perform reasonably well in the field. Specific service modes tailored for single sideband transmission may present further improvements and are under consideration for this concept. However, new service modes require receiver updates to the installed receiver base.

With single sideband configurations, it is also possible to create various narrow band modes, such as a 400 kHz mode by turning off the outermost sets of carriers from the basic 600 kHz configuration. The 400 kHz mode in figure 4c also demonstrates that we can switch sidebands A and C and return to 200 kHz tuning steps and no longer require European tuning modes in the receiver. The 400 kHz mode also fits nicely into existing channel allocations.

Turning off sidebands B in figure 4c leads to a 200 kHz solution as sown in 4d. In this case it makes sense to switch the single sidebands again in order to condense the dialing positions. The proposed method is highly flexible in occupied bandwidth particularly when utilizing single sideband modes allowing it to be integrated into existing FM channel allocations with minimal frequency repacking.

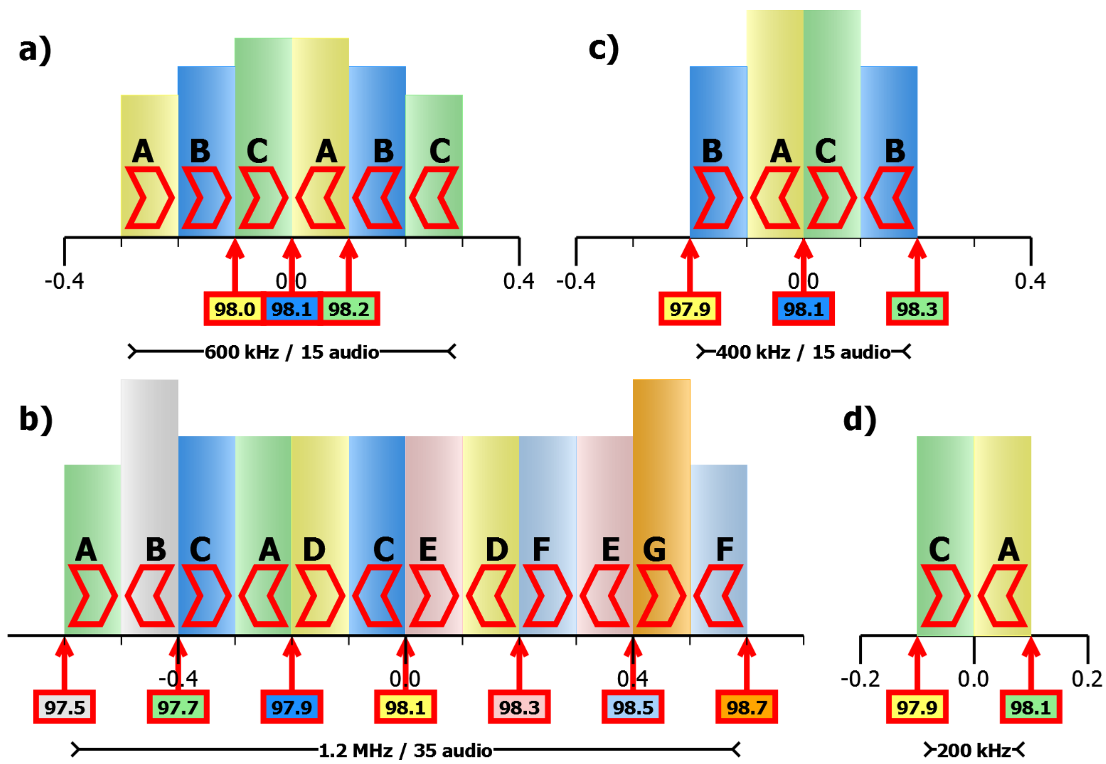

Fig. 4. Example interleaved IBOC signals for 200 kHz, 400 kHz, 600 kHz and 1.2 MHz bandwidth. Stations are indicated by color and letter code. Lower and upper sidebands are indicated via arrows and the corresponding radio tuning frequency is shown.

F. Receiver Considerations

The big benefit of the proposed method is that it builds upon existing HD Radio receiver products available today and receivers already in the field. Since this is a new signal configuration not specifically tested in today's receiver products, we need to look at signal compatibility with existing HD Radio receivers.

The HD Radio receiver picks out only the sidebands of interest within the multiplex and rejects all others. The receiver will ignore the carriers located in the FM space and once it detects the presence of an all digital service mode mutes the non existent FM audio transmission. The FM signal possess a more constant power envelope even taking frequency selective fading into account compared to IBOC. Therefore, HD Radio receiver manufacturers are advised to implement conservative Automated Gain Control (AGC) loops leaving headroom to account for signal peaks in the intermediate IBOC carriers in order to avoid signal clipping. IBOC receivers must be able to reject up to 20 dB (100x) the FM power for standard hybrid service modes today. This means that IBOC receivers must be built with sufficient resolution in the front end and down conversion to decode a low level IBOC signal already. As a preliminary guideline the author recommends to not exceed more than 10 dB signal power for any inner IBOC carrier combination until more receivers are tested with this new signal configuration.

No matter how wide the broadcast signal's occupied bandwidth configuration, the IBOC receiver will only select the 400 kHz of signal bandwidth required for the selected audio channel. Compared to DAB or DVB with wider occupied bandwidths, this should lead to lower cost HD Radio receiver implementations. HD Radio receivers today are already built to handle high 2nd adjacent channel D/U ratios outside the 400 kHz desired bandwidth. In the field, very low second ajacent hybrid IBOC D/U ratios are common, so elevated carriers, such as subcarriers B and G in figure 4b should have little impact on the reception of stations C and F in the 1.2 MHz multiplex.

All HD Radio receivers are designed to work with the standard hybrid signal modes and the all digital service modes MP5 and MP6. Yet, some receiver implementations still exhibit a dependence on the FM carrier for scanning stations. These types of receivers are required to be tuned manually. Even with HD scan capability many receivers only stop on the first IBOC station they encounter and the remaining stations still need to be tuned manually. The author questions the consumer experience of station scanning as we expand the total number audio offerings. Perhaps an application level electronic program guide and station reference presents a better alternative to new station discovery.

IV. Improved Spectral Efficiency

The following sub-sections detail the chief factors that contribute to the improved spectral efficiency of all digital IBOC transmission compared to FM: better audio capacity per kilohertz of occupied bandwidth, better protection ratios

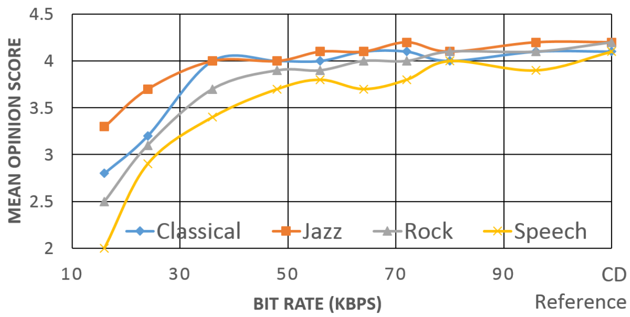

Fig. 5. Listener evaluation of HD Codec audio performance [14] over various bit rates. A mean opinion score of 5 represents the best perceived audio quality and 1 the worst.

between desired and undesired IBOC transmissions, and better frequency packing through multiplexing a number of IBOC signals that ensure consistent adjacent channel ratios and maintain carrier orthogonality between adjacent stations.

A. Audio Capacity

Comparing IBOC audio service with FM audio service is highly subjective due to the difference of audio impairment. FM audio with limited 15 kHz audio bandwidth can be made to sound good using today's audio processing technology. Often dynamic audio range is compromised in order to get the loudest sounding station on the dial. FM also suffers from signal propagation related distortion that generally increase with a drop in signal strength and under multi-path conditions. It is difficult to say what the average FM audio impairments to the average listener are, but it is clear that much of the listening is done beyond the protected contours at field strengths as low as $42dB\mu V/m$ [8].

The dynamic range of HD Radio audio is superior since its loudness can be controlled via digital scale factors that are broadcast over the air not requiring aggressive audio processing. HD Radio audio also does not degrade with signal quality until close to signal breakdown and intermittent bit errors are mitigated via error concealment often with little impact to the underlying audio. Since the HDC codec used in HD Radio is a perceptual codec, lower audio bit rates will preserve less of the original audio content. Looking at the data capacities in table I, we want to formulate rough guidelines comparing audio capacity between FM and HD Radio. Fortunately, listening research was conducted by Dr. Ellyn Sheffield evaluating the effectiveness of the HD codec at varying bit rates [14]. In this report Sheffield states that most respondents in the survey could no longer discern the audio quality difference of audio clips encoded above 48 kbps. Figure 5 reproduces the mean opinion scores she found for classical music, jazz music, rock music and speech. A mean opinion score of 5 is the best score and a score of 1 is the lowest or worst sounding audio. These scores should be viewed with respect to the unimpaired CD reference material. Classical and jazz show little degradation down to bit rates as low as 36 kbps. Rock is starting to show some noticeable, but likely tolerable, impairment at 36 kbps. Speech is the most likely content to produce noticeable impairment and the report breaks this category down to male and female speech samples with a somewhat greater degradation in female speech.

These test have been conducted with the HDC codec at full stereo. Fortunately, there are two other audio modes that can be employed at low bit rates: mono and parametric stereo. Speech impairment can be minimized by choosing a mono broadcast mode, since most spoken content has little stereo separation. The author asserts that with mono transmissions the total bit energy can be dedicated to a single channel effectively doubling these results. For example, a 24 kbps mono transmission effectively turns into 48 kHz quality where speech still shows little impairment. Parametric stereo down mixes the stereo source material to mono, but maintains side information for spatial intensity stereo generation and ambiance regeneration at the decoder. Typically the side information is coded in an additional 2-3 kbps channel [15]. The author assert that we should be able to expect at least 50% improvement in bandwidth utilization compared to full stereo. This turns 24 kbps audio into 36 kbps or better audio.

	MP5		**MP6**	
	channel / rate (kbps)	mode	channel / rate (kbps)	mode
HD-1	P1-24	parametric	P1-24	parametric
HD-2	P2-32	stereo	P1-24	parametric
HD-3	P2-24	parametric	P2-32	stereo
HD-4	P2-17	mono	P2-16	mono
HD-5	P3-24	parametric		

TABLE III: Example Audio Allocations

Table III shows exemplary audio allocations for the all digital service modes MP5 and MP6 that maximize the number of audio offerings and is to be taken as an upper limit for the number of possible audio offerings. Given the increased audio capacity described in this paper, it is likely that the value proposition favors higher audio quality and most station will operate with 3 or 4 audio streams and additional data services. Since the combined 200 kHz of IBOC bandwidth equals that allocated to FM, the spectral efficiency of IBOC is roughly 4-5 times that of FM. This increase in spectral efficiency is already leveraged in hybrid IBOC broadcasting today with around 1700 multicast stations available in the US today [3].

B. All Digital Protection Ratios

Today's FM allocations typically require a 20 dB protection ratio at a station's protected contour [16] and for higher fidelity FM audio even better ratios are desired. This limits the ability of frequency reuse within the FM band. For hybrid operating modes, the co-channel D/U ratios are already well understood. Kean [16] has already shown that IBOC only requires a 4 dB co-channel D/U ratio under steady signal conditions regardless of received signal strength. When subject to a Trimmed Urban Fast Rayleigh fading profile (60 km/hr) it was found that an

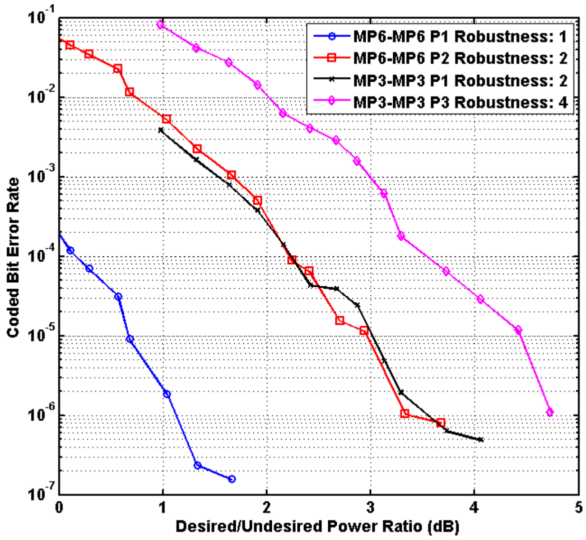

Fig. 6. Bit error rates for MP3 vs. MP3 and MP6 vs MP6 interference for steady signal conditions. The highest robustness channel P1 of MP6 provides 2.5 dB coding gain over MP6 P2.

additional 3 dB margin was required for solid IBOC reception. Under Raleigh fading conditions, up to 8 dB additional margin is required as the received signal strength dropped to -60 dBm. In hybrid co-channel interference, the desired IBOC sideband directly interferes with the undesired IBOC sideband so it is not unlike all digital interference.

For hybrid service modes, the analog FM presents a fall back option once the digital signal breaks down. Because of the time and frequency diversity between the IBOC carriers and the FM carrier, there exists a likelihood that at digital signal breakdown, the FM carrier is still present and contributes positively to the overall availability of the main audio. Referring to table I we recognize that the all digital service modes MP5 and MP6 have channels with the highest robustness level 1 in order to compensate for the loss of the FM fallback. MP5 and MP6 add parallel transmission of the P1 logical channel with 1/2 rate coding that is shifted in time to add more time diversity as shown in figure 7. This creates a fall-back channel similar to the FM in hybrid transmission.

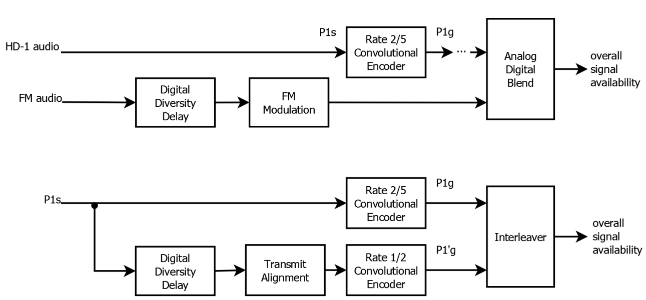

Fig. 7. Top: MP3 with analog fall back, bottom: MP5/MP6 Dual coded P1 channel [11]

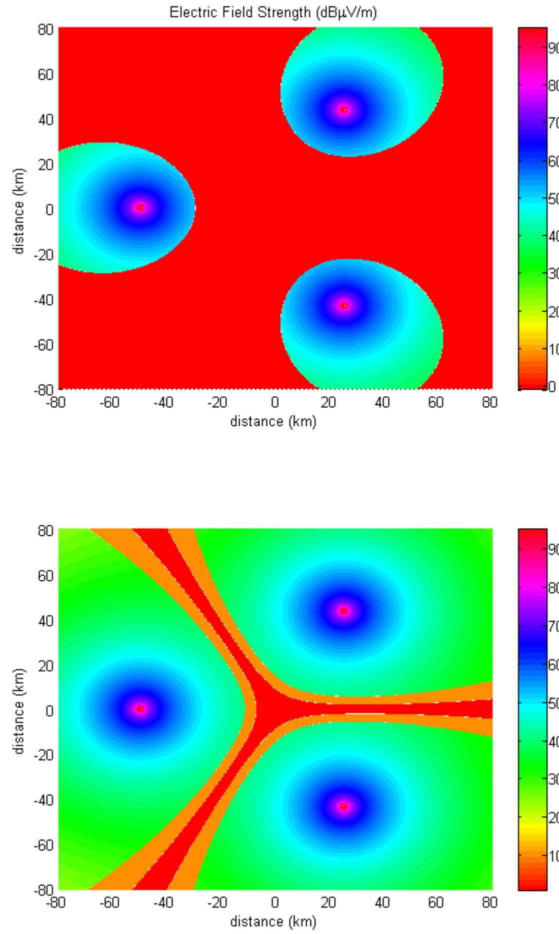

Fig. 8. Short spaced co-channel interference zones - top: 20 dB D/U Ratio used for FM provides 31.6% coverage, bottom: mobile MP6 at 4.5 dB D/U (orange) and steady signal reception at 1.5 dB (red) provides 83.2% to 93.6% coverage

Since the gains of this additional coding is not well understood, our lab conducted coded bit error tests on audio streams placed on the MP6 P1 and P2 partitions with robustness level 1 and 2 respectively. The output of two IBOC transmitters were coupled in a 3 dB splitter and the combined output was fed into an iBiquity IBOC test receiver capable of displaying coded bit error rates on all logical channels. The two IBOC modulators were configured to produce a deterministic bit pattern for the receiver to compute the bit error rate on. Relative power levels were measured using the integrated power readings of a spectrum analyzer. For the purposes of this test only a single set of sidebands was tested with both transmitters configured for either MP6 or MP3 without an FM carrier.

For comparison to Kean [16] MP3 was tested on its P1 and P3 partitions with robustness levels 2 and 4 respectively (please refer to table I for robustness levels). The results are plotted in figure 6. The MP3 P1 results shows few bit errors above 4 dB D/U even the few remaining bit errors can be concealed in the underlying audio and are barely noticeable. Listening is possible well below the 4 dB level with increased frequency of concealed errors and short dropouts. At the 3 dB level audio is impaired about every 10 s and at 2.5 dB the receiver has trouble acquiring and keeping the channel. The P3 channel behaves much the same, but requires an additional 1.5 dB of D/U. This in part explains why audio placed today on P3 carriers does not carry as far as the main audio.

The MP6 P2 partition is also marked as robustness level 2 with a 2/5 convolution encoder, just like the MP3 P1 partition. The results in figure 6 confirm that both logical channels have the same performance as expected. The interesting aspect is the MP6 P1 channel with the highest robustness mode. The additional time diverse data stream does in fact provide coding gains up of to 2.5 dB. MP6 P1 can operate very well into a 1.5 dB D/U without impairment. The receiver can acquire the signal with as little as 0.5 dB D/U albeit it takes longer to lock. Once the receiver has locked and is producing audio, we have been able to increase the undesired transmitter to up to 5% above the desired power level. The receiver maintained lock and produced impaired audio.

From these results, we conclude that any logical channels with robustness level 1 require a 1.5 dB D/U, robustness level 2 requires a 4 dB D/U, and robustness level 4 requires at least 5.5 dB D/U. For all cases, we should add a 3 dB fading margin for mobile reception as stated above. These results are stated in table IV. With these results we can create a simple model to compare the impact on coverage. Just for demonstration purposes, the Okumura-Hata model for signal propagation as described in International Telecommunication Union (ITU) recommendation P.529-3 [17] was used to compute the electric field strengths at a distance from the transmitter. The received power from one transmitter versus another transmitter can be computed assuming a unit receive antenna gain and compared against the above stated D/U limits. Figure 8 shows a hypothetical short spaced setup of 3 transmitters on a 50 km radius circle that places them 87 km apart. Each transmitter is transmitting at 6 kW at 100 m above average terrain and a receiver height of 1.5 m is assumed. The top plot shows the potential FM interference zones where not a single transmitter exceeds a D/U of 20 dB or better above the combined undesired signal power. The exercise is repeated with the D/U ratios found above for MP6 P1 and P2 channels and the covered area is totaled. The results are presented in table IV. Note that the Okumura-Hata model is valid 50% of the time for 50% of locations.

The FM geographic availability of 31.6% intuitively makes sense given that even in big markets we typically have no more than 30 receivable stations on the dial across 100 channel allocations of 200 kHz each. Using digital transmission the same short spaced setup could cover up to 93.6% of the simulated area with stationary coverage; almost a three fold increase. Once fading and lower robustness levels are considered, the covered area drops to 70-80%, still far better than FM. Since coverage is typically planned around population centers, the

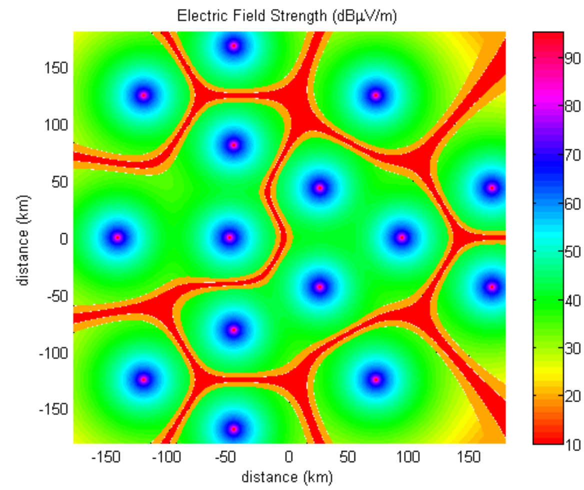

Fig. 9. Example cell based network of independent 6 kW HD multiplex transmitters with two distinct SFN networks broadcasting identical content.

population coverage will be greater than the results listed in table IV.

Channel Type	Robustness Level	Desired / Undesired	Geographic Availability
FM		20 dB	31.6%
MP5 P3	4	8.5 dB	68.8%
MP5/6 P2	2	7.0 dB	74.0%
MP5/6 P1	1	4.5 dB	83.2%
MP5/6 P1 (stationary)	1	1.5 dB	93.6%

TABLE IV: Simulation Geographic Coverage Results

These results form a compelling argument for moving towards all digital transmission. While hybrid operation is maintained, we do not benefit from improved spectral efficiency, since the FM will always be the limiting factor for planning purposes.

C. Single Frequency Networks

The results in table IV indicate that as the robustness of the signal improves total geographic coverage increases and with it the spectral efficiency. In theory, once we achieve a D/U ratio of 0 dB all interference zones disappear and as a receiver moves from the coverage from one transmitter to the next, it would simply switch from one transmission to the next. This would achieve optimal spectral efficiency. However, this blatantly ignores the impact of terrain variations and shielding. In a mobile environment with location variability the receiver may toggle between two co-channel transmissions.

If the content across the two transmissions is identical, one may consider joining the two transmissions in a single frequency network and largely eliminate interference in between. To do so, the incident wavefronts from two (or more) transmitters must be aligned in time in the interference zone, which coincidentally is defined by the same D/U ratios shown in table IV. The 3 dB fading margin should be considered since both signals will fade independently. Figure 9 indicates the potential interference zones between transmitters in orange and red in a matrix of 6 kW transmitters. Two groups of transmitters have been joined to show how SFNs can be used to tailor the intended coverage area. Small on channel boosters can be used to address localized interference zones.

The IBOC signal provides a $75\mu s$ guard interval between symbols representing 22.5 km distance over which the timing of the two incident transmissions can be aligned at the receiver. Bit error tests conducted in our lab indicate that once real world signal degradations are taken into account a more conservative $40\mu s$ should be taken for planning purposes in key areas. FM SFNs in comparison require $5\mu s$ time alignment within the much larger interference zone defined by a D/U ratio of 20 dB.

National or wide area coverage can be achieved using SFNs if the timing propagation is carefully considered. Depending on the geography, it may be necessary to employ terrain shielding and characteristics along with additional small scale boosters to accomplish this feat. The most efficient use of spectrum is to maximize the use of SFNs. In many cases whole matrices of allocated FM frequencies dedicated to translators of the same program could be re-claimed and re-purposed.

A complete SFN build out across the entire band may be spectrally efficient, but would mean terrestrial radio loses one of its main strengths, local content. Considering that with robust all digital transmission modes we approach the geographic availability of SFN, the value of SFNs in terms of spectrum efficiency is diminished. Of course, it is possible to design a SFN and have individual nodes join and leave the SFN for local day parts, as long as, all services on the given IBOC signal can tolerate the split. Due to the high FM protection ratios this has not been a real option in FM SFNs.

D. Frequency Reuse Patterns

In all digital transmission, it is possible to control the location of co-channel interference by managing the sideband power levels of adjacent transmitters. Figure 10 shows the 600 kHz HD Multiplex described above and steps sideband pairs down by a fixed amount, such that when two sidebands across neighboring patterns are of equal power and create interference the third sideband exhibits a large delta. This ensures reception of at least one IBOC station everywhere. For example, if we assume a 3 dB delta and station B and C of the first and second frequency reuse pattern are received at the same power levels, then station A will exhibit a 9 dB delta and should be received unimpaired.

This technique does not improve spectral efficiency overall, but rather it ensures geographic coverage of at least one IBOC station. If it is a mandate that everyone be covered with a set of national services and provide regional services, then the national services could be placed on the dominant carriers and regional services on the lower sidebands.

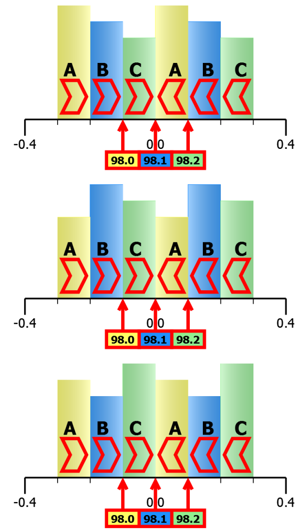

Fig. 10. Sideband power levels can be managed to control interference zones to ensure reception of at least one station when other sidebands are interfering. Three frequency reuse patterns can be used on neighboring transmitters.

E. Frequency Packing

Audio capacity, improved protection ratios, and SFN capability are all properties of the IBOC signal standard. While IBOC is used in a hybrid signal configuration, all these aspects are limited by the FM signal properties. The HD multiplex concept described in this paper provides a practical means of implementing an all digital IBOC standard. The benefits of HD multiplex go further than that. Since the multiplex is combined within a single transmitter and broadcast through a single antenna system, the relative signal levels to other sidebands are also fixed subject only to frequency selective fading minimizing 1st and 2nd adjacent interference concerns for stations on the multiplex. Optimal spectrum utilization is achieved as no frequency guard space is required within the HD Multiplex. It is not recommended to interleave IBOC from different transmitters, since the relative levels of sideband groups cannot be guaranteed due to differing antenna radiation patterns. It is possible to saturate the receiver with too much adjacent sideband power if the desired transmitter is going through an antenna null. It is possible to butt adjacent transmitters together without interleaving signals at the same transmission site if the exciters are synced and antenna patterns are carefully considered.

V. Application Areas

Taking the above points into account, the proposed concept of transmitting an all digital HD multiplex signal by interleaving indvidual stations can find application in the following areas.

A. Maximizing FM Band Capacity

The spectral efficiency of all digital transmission has been demonstrated thus far. Table V applies these results to the FM band (88-108 MHz).

	max audio services	expected max	
		audio services	aggregate data capacity
Typical FM	30	25	30 kbps
Hybrid FM+IBOC	150	75	630 kbps
HD Multiplex	345	207	1.7 Mbps
Extended FM Band	206	124	1.0 Mbps

TABLE V: Estimated Band Capacity, FM with 1.2 kbps RDS, expected IBOC 3 good quality audio with 24 kbps data

The first column shows the typical number of FM stations on the dial of a major market today. Not all of these stations may be received well and not all stations may even be picked up by a receiver scan. So the expected maximum number of radio stations is taken as 25. Assuming each station also broadcasts 1.2 kbps of Radio Data System (RDS) data, we achieve an aggregate data capacity of 30 kbps. Using today's hybrid FM+IBOC technology it is possible for each station to add up to 5 parametric audio streams at bit rates around 24 kbps (see table I). This represents somewhat of an absolute maximum case. As the number of available audio streams increases, it is expected that stations may favor higher bit rates to differentiate themselves and add additional data services. The expected maximum case assumes 3 audio streams at 32 kbps each and 24 kbps dedicated to data services that may be broken down into 5 kbps each for graphical data, such as album art, and possibly another 9 kbps for traffic data. Note that a complete build out of HD Radio on every station could lead to a 26% reduction [6] in analog coverage. This is not considered here and would reduce the total number of station availability.

Assuming the FM band could be converted to HD multiplex in its entirety, the absolute maximum number of audio services receivable in a given market could increase ten fold. This assumes that a total of 33 HD multiplex 600 kHz wide pseudo-channels could be supported in the band from 88 to 108 MHz. Using a conservative 68.8% area coverage for the P3 partition from the results in table IV, we could expect an average of 23 receivable HD multiplex signals each with up to 15 audio services for a total of 345 available audio services. This maximum case is only achievable with optimal frequency planning and dedicating all bandwidth to low bit rate audio services.

More realistically, higher bit rates and data services will be allocated. This still leaves around 207 audio services at 32 kbps operating in stereo or parametric stereo. If each HD multiplex broadcasts 3x24 kbps we achieve an aggregate data rate of 1.7 Mbps. Note that a receiver would only receive the data portion that it is tuned to. With many dual tuner systems available specifically in automotive receivers, the second tuner could scan the band just like many traffic receivers are today. With increased data capacity across the band, specific data can be repeated more frequently making data appear on the receiver more responsively.

The above numbers may present a long term goal, but it is not realistic to propose switching the entire band over to HD multiplex at this time. With the flexibility offered by HD multiplex it can be inserted into the existing frequency allocations. Especially, rural areas can often find sufficient space for a local HD multiplex offering diverse audio services to smaller markets.

It may be reasonable to consider a partitioned FM band where with careful frequency re-packing of existing stations enough space could be found for a 600 kHz HD multiplex configuration. Some countries or jurisdictions can consider replacing an entire matrix of frequencies allocated to FM translators for national broadcasts with a single HD multiplex operating in an SFN configuration. Possibly this frequency band can be dedicated in whole or in part to HD multiplex use. Maintaining hybrid operation in the short term will allow enough receivers to be fielded. Additional services may only be available on HD multiplex.

B. *Extended FM Band*

In cases where the FM band is too congested to be partitioned, the extended FM band can be considered where TV channels 5 and 6 located at 76-88 MHz are joined with the rest of the FM band as proposed in Brazil [18]. A vacant spectrum could be planned optimally from the start without requiring frequency re-packing. Table V shows the additional capacity the extended FM band could provide. At 124 audio services and 1 Mbps of data the added spectrum could very well supplement the FM band. Adapting new receivers to accommodate the extended FM band is a manageable task considering that some countries, such as Japan are already utilizing the extended FM band. IBOC receiver chipsets, such as the Silicon Labs Si4622 [19] among others, already support the world wide FM band (76-108 MHz). Yet few IBOC receiver products in the field today have extended FM band product support.

There exists an interesting intersect between TV channel 6 and FM receivers. When looking at a cross section of IBOC receivers a good number support European tuning modes down to 87.5 MHz. At the time of writing, according to the Federal Communications Commission (FCC) database, only a single full service FM station (KSFH) and one FM translator (K200AA) are allocated below 88.1 MHz [20]. This provides a 600 kHz space for the basic HD multiplex signal configuration allowing receivers to tune in at 87.5 MHz, 87.6 MHz, and 87.7 MHz. A U.S. nation wide HD multiplex network is possible that may also be extended into Canada and Mexico.

Only nine full power TV stations on channel 6 are registered in the FCC database [20]. If these stations cannot be moved, it is feasible to add two or more single IBOC sidebands to the upper end of the Advanced Television Systems Committee (ATSC) spectrum as an ancillary audio service to the channel 6 TV broadcast much in the same way as the FM carrier in an analog National Television System Committee (NTSC) signal.

It is an attractive proposition to extend the FM band starting with the existing receiver base with an eventual build out to 124 to 206 audio services across channel 5 and 6.

C. AM Translators

An AM Radio Revitalization Report and Order is on circulation at the FCC intending to address and help the state of AM broadcasting today. A current proposal before the FCC proposes the option to relocate an AM station's translator on the FM band by up to 250 miles [21]. For many AM stations, the cost of the FM translator is a serious consideration and is often out-of-reach for smaller AM stations. With the increased translator radius it may be possible for several AM stations to operate an HD multiplex transmitter together in a mutually beneficial location. Additional channel capacity may be leased out to finance the operation of the transmitter.

If a widely available frequency allocation is used, such as the 87.3-87.9 MHz window explained above, then an all digital HD multiplex network could be built covering a large area with many transmitters in a cell grid similar to figure 9. If multiple translators are allowed, AM stations can match their AM coverage area by choosing the appropriate HD multiplex translators. Some nodes in this network could also operate in a SFN configuration.

The channel 6 space of 87.3-87.9 MHz could be dedicated to AM translator use today with an eventual build out across all of channel 6 as a permanent home for AM broadcasters. AM transmission may continue while listener demand is justified.

D. Reduced Transmission Cost

When looking at the transmission cost of today's hybrid HD Radio configuration, many station operators are quick to point out the increased transmission cost. This encompasses transmitter conversion costs, licensing costs and a reduction in energy efficiency. A state of the art FM transmitter can operate at power efficiencies of 72% AC-RF, but this efficiency drops to 52% AC-RF when broadcasting a hybrid FM+IBOC signal at -10 dBc IBOC injection [22]. Table VI shows a typical 10 kW transmitter operating in FM mode with an annual operating cost of $12,945 based on a energy rate of 10.64c/kWh across all sectors [23]. This accounts for a single audio transmission only. Scaling to 15 audio streams requires an annual energy bill of $194,180.

When switching to hybrid FM+MP3 transmission, the transmitter operating costs go up, because 1.2 kW additional RMS power is required with a drop in transmitter efficiency. It is clear that while operating in hybrid, operating costs do go up unless effective use of the additional capacity offered by IBOC is made. Once the station builds out to 4 or 5 audio streams the per stream cost drops to $3,796. When operating in all digital mode using HD multiplex, the transmitter efficiency drops further to an estimated 45%, but less RMS power is required to achieve equivalent FM coverage. In hybrid operation, it has been found that IBOC at -10 dBc injection provides comparable FM coverage [6]. This means we can drop our 600 kHz HD multiplex power to 3 kW since it is composed of three stations. However, MP5 has 40% more power compared to hybrid MP1 bringing the required HD multiplex power to 4.2 kW. The overall transmitter operation is cut in half from hybrid transmission and the audio capacity is increased to 15 audio streams as per table III bringing the per audio stream cost to $580 annually; less than 5% of the FM audio service cost. MP6 is also shown for comparison purposes. Note that with the increased robustness of MP5 and MP6 the assumption of comparable FM coverage at 10% power is conservative.

	Hybrid		HD Multiplex	
	FM	MP3	MP5	MP6
RMS Power (kW)	10	11.2	4.2	4.2
AC-RF Efficiency	72%	55%	45%	45%
Total Power (kW)	13.9	20.4	9.3	9.3
Operating Cost ($)	12,945	18,980	8,699	8,699
Audio Services	1	5	15	12
Per Service (kW)	13.9	4.1	0.62	0.78
Service Cost ($)	12,945	3,796	580	725
15 Services ($)	194,180	56,941	8,699	10,874

TABLE VI: Transmission Energy Savings

Other savings result from reduced transmitter, site and antenna capital and maintenance costs. In many cases existing broadcast infrastructure such as antennas and transmitters can be re-used. For example, a modern hybrid FM+IBOC transmitter operating at -10 dBc injection can be converted to HD multiplex operation. Due to comparable FM coverage most transmission sites are expected to be used for this application, as well.

Any broadcaster or group of broadcasters with varied content or languages across a number of audio streams stand to benefit from the method presented in this paper. National coverage can be achieved using the SFN approach shown in section IV-C and regional content can be broadcast when SFN nodes break into independent transmissions using one of the frequency reuse patterns shown in section IV-D. Overall, the proposed signal provides one of the most cost effective migration solutions to all digital broadcasting.

E. IBOC Channel Combiner

While many of the aspects discussed thus far require regulatory consideration, there is one aspect of the proposed method that may be applicable in todays regulatory environment. Suppose, we take the 1.2 MHz wide signal in figure 4, but we only enable carrier sets A and F. The combined signal can be broadcast using a separate antenna as is commonly done when space combining FM and IBOC transmissions, but now the IBOC transmission shares the antenna. The 800 kHz separated FM transmissions would be maintained on their respective antennas. This saves the cost and space of an additional channel combiner and one larger more efficient transmitter can do the job of two smaller ones. One can consider placing one of the FM carriers within the HD multiplex and broadcast it along with the remaining digital carriers. This setup would not be unlike PAPR reduction of a hybrid FM+IBOC signal [10]. Now this approach only requires two antennas across two hybrid FM+IBOC stations.

If allocation rules allow, carrier set D can also be enabled in an all digital MP5/6 configuration. This also demonstrates that a 400 kHz channel combiner is possible using this method. Another analog carrier could be placed on a separate antenna in between carriers D. Note that only a single FM carrier can be part of the multiplex as two FM carriers would start to beat with one another and degrade the PAPR reduction performance.

As HD multiplex is developed over ever larger signal bandwidths more and more of the FM band can be covered this way allowing for multiple stations to share a single IBOC transmitter. It is conceivable that large portions of the FM band, such as the Non-Commercial Educational (NCE) band, can be covered this way in the future. Transmitter linearity will be a challenge for this type of signal especially under increasing bandwidth constraints. While a solid block of IBOC carriers needs to consider spectral re-growth outside its occupied bandwidth, the in-band spectral re-growth is of secondary concern and has little impact on the broadcast signal. As sidebands are turned off leaving unoccupied spaces spectral re-growth must be considered in those areas. In general, transmitter linearity will be an important aspect for HD multiplex.

VI. Conclusion

Transforming today's FM broadcast environment from a single purpose transmission system to a shared use all digital IBOC HD multiplex system described in this paper addresses these major broadcast challenges: improved spectral efficiency for more audio services in congested urban centers and lower transmission costs for small market and national broadcasters. The per audio service energy cost can be as low as 5% compared to an FM broadcast with additional savings in broadcast equipment infrastructure and maintenance. Simulations shown in this paper suggest a ten fold increase in available audio services can be achieved if the entire FM band is converted to HD multiplex use.

Through flexible configuration modes HD multiplex can be inserted into existing FM frequency allocations and the same tri-mode HD Radio receiver sets available today can tune to FM, FM+HD, or HD multiplex. Stations close in frequency can share an HD multiplex as an IBOC channel combiner today with a hybrid FM+IBOC signal configuration.

Optimal spectrum use is made by partitioning the FM band with the possibility of extending the FM band into TV channels 5 and 6 (76-88 MHz) for HD multiplex. A national HD multiplex network across the U.S. carrying into Canada and Mexico is feasible at 87.5-87.7 MHz with many existing HD Radio receivers supporting European tuning modes; a good application for AM translator use. Eventual build out across channel 5 and 6 will enable more than 100 additional audio services with IBOC receiver chipsets supporting the extended FM band today. The increased aggregate data capacity will lead to new and innovative data services.

The hybrid FM+HD build out is taking hold in the United States and internationally with over 25 million receivers and thousands of stations transmitting the signal. Now is the time to plan for full digitization of the FM band and maintain its original purpose of sound broadcasting.

Acknowledgment

The author would like to thank Brian Walker for his input, comments and review along with other colleagues for their input. I would also like to thank Eric Hamilton for collecting the lab data on IBOC performance.

References

[1] D. Moro, "FM Switch Off Plans Shift from Country to Country," *Radio World*, July 2015.

[2] "Digital Radio Action Plan," Department for Culture, Media and Sport, Tech. Rep., January 2014.

[3] "iBiquity Digital Radio Website," http://www.ibiquity.com, accessed: Aug 12, 2015.

[4] *NRSC-5-C In-band/on-channel Digital Radio Broadcasting Standard*, National Radio Systems Committee Std., September 2011. [Online]. Available: http://www.nrscstandards.org/SG/NRSC-5-C/NRSC-5-C.pdf

[5] J. Warner, "Economics of DAB+: Broadcasting: Use it or lose it," accessed: Aug 13, 2015. [Online]. Available: http://wp.me/p3cW7t-h3

[6] "Digital Radio Coverage & Interference Analysis (DRCIA) Research Project," National Public Radio, Final Report to the Corporation for Public Broadcasting, July 2008.

[7] *Digital Audio Broadcasting (DAB); Signal strengths and receiver parameters; Targets for typical operation*, European Telecommunications Standards Institute Std., November 2000.

[8] "DAB Coverage Planning," Ofcom, Tech. Rep. [Online]. Available: http://stakeholders.ofcom.org.uk/binaries/broadcast/radio-ops/coverage/DAB_Statement.pdf

[9] P. J. Peyla, "The structure and generation of robust waveforms for fm in-band on-channel digital broadacsting," iBiquity Digital Corporation, Tech. Rep.

[10] P. Schmid, "An Improved Method of Peak-To-Average Power Ratio Reduction for FM+IBOC Broadcast Transmission," Masters report, Dalhousie University, 2009.

[11] *HD Radio^{TM} Air Interface Design Description - Layer 1 FM*, National Radio Systems Committee Std., August 23, 2011, rev. G.

[12] *HD Radio^{TM} FM Transmission System Specifications*, National Radio Systems Committee Std., August 24, 2011, rev. F.

[13] B. Sklar, *Digital Communications: Fundamentals and Application*, 2nd ed. Prentice Hall, 2001.

[14] E. G. Sheffield, "Perceptual tests of ibiquitys hd coder at multiple bit rates," Sheffield Audio Consulting, Tech. Rep., 2004, prepared for National Public Radio.

[15] Wikipedia: Parametric stereo. [Online]. Available: https://en.wikipedia.org/wiki/Parametric_Stereo

[16] J. Kean, "An Improved Coverage Prediction Method for HD Radio," *Broadcast Engineering Conference*, 2008.

[17] *Prediction Methods for the Terrestrial Land Mobile Service in the VHF and UHF Bands*, International Telecommunication Union Recommendation, ITU-P529-3.

[18] C. E. Behrensdorf, "Brazil Broadcasters Push AM Migration," *Radio World*, November 2013. [Online]. Available: http://www.radioworld.com/article/brazil-broadcasters-push-am-migration/222179

[19] *High-Performance, Single-Chip FM HD-Radio^{TM}/RDS/RBDS Data Receiver*, Silicon Labs, March 2015, Si4622-A10.

[20] FCC Database. Accessed: Sept 21, 2015. [Online]. Available: https://www.fcc.gov/data/search-gallery

[21] S. Ashworth, "FCC Staff Considers Translator Relocation Option for AM," *Radio World*, Sept 2015. [Online]. Available: http://www.radioworld.com/article/fcc-staff-considers-translator-relocation-option-for-am/277054

[22] *GV10 FM Transmitter Specification*, Nautel Ltd., issue 0.7.

[23] Average Price of Electricity to Ultimate Customers by End-Use Sector. U.S. Energy Information Administration. Accessed: Sept 22, 2015. [Online]. Available: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a