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In-band, on-channel digital sound (System C) transmission systems: Considerations for operational installations

BS Series

Broadcasting service (sound)

International Telecommunication Union

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REPORT ITU-R BS.2503-0

In-band, on-channel digital sound (System C) transmission systems: Considerations for operational installations

(2022)

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1.1 Introduction

In-Band, On-Channel (IBOC) digital sound broadcasting, defined in Recommendation ITU-R BS.1114 as Digital System C, operates within the United States Federal Communications Commission (FCC) allocated frequency modulation (FM) band. This digital sound broadcast technology operates within the FM band (In-Band) while making use of existing broadcaster analogue channel assignments, thus establishing the IBOC digital radio broadcasting (DRB) system.

IBOC broadcast technology allows broadcasters to add digital signals to their existing analogue broadcasts, providing the capability for an eventual transition to digital-only. Two modes define how audio and data are transmitted in the IBOC system: 'hybrid' and 'all-digital'. The Hybrid mode includes both existing analogue and new digital services. Broadcasters are using this mode during rollout of IBOC digital radio technology to permit analogue-only radio receivers' continued operation. In the future, when the marketplace is sufficiently saturated with IBOC receivers, broadcasters can switch to the all-digital mode. Hybrid receivers employing IBOC technology are backward and forward compatible, allowing them to receive current analogue broadcasts in addition to all-digital broadcasts.

1.2 Conversion to digital technologies

The IBOC digital sound broadcast system was designed to provide a unique opportunity for broadcasters and consumers to convert from analogue to digital broadcasting without disruption of the legacy analogue broadcast service while maintaining the current radio stations' existing dial positions. Consumers who purchase digital radios receive AM and FM stations broadcasting with digital signals with digital sound quality. Additionally, consumers can receive new multicast audio channels and wireless data services rendered on a radio's display screens, like those offered on Internet-connected devices like smartphones. Programme service data (PSD) such as artist, title, programme content, news, sports, local traffic and weather are available today.

Further details of the technical system definition are provided in Recommendation ITU-R BS.1114. Additional feature examples and field test reports are documented in Report ITU-R BS.2384.

2 IBOC broadcast system development concepts

The IBOC broadcasting system represents the next generation of broadcasting in the AM/FM bands. Existing analogue AM and FM broadcasting modes may be augmented, and even replaced, by digital broadcasting modes, resulting in improved and expanded services to the consumer, that heralds a new generation of broadcasting equipment. This section provides an overview of the IBOC system design concepts, and what it means to the next generation of broadcasting systems.

The IBOC broadcast system concept encompasses all the features currently envisioned for IBOC digital systems for near-term and longer-range development. Features being developed are broad in concept and have a wide range of appeal to both the service provider and the consumer.

Initially, broadcast systems will support processing and transmission of analogue and digital audio signals and digital data services. As the IBOC system evolves, broadcasters will become more innovative in their use of the digital transmission for new services and applications. System design concepts are modularized and grouped, for discussion, according to features or services offered. Those features are listed and described in the following paragraphs.

It is anticipated that broadcast system designers and developers will independently determine the features incorporated in the various IBOC broadcasting equipment models offered based on the services supported by broadcasters and on consumer demand.

2.1 IBOC system features

Flexibility in the selection of services was an important objective of the IBOC system development. Individual broadcasters may elect not to offer all services nor expeditiously update their capabilities as the system evolves. The IBOC broadcast system will support a wide array of receiver and broadcaster configurations to accommodate user preferences.

IBOC Technology offers improved audio quality and services over existing analogue systems. In the FM band, IBOC provides compact disk (CD) like audio quality. In the AM band, it will provide audio quality like that of existing analogue FM. IBOC Technology can offer new audio features, such as surround sound, not practical with existing analogue services, and will support multiple audio programs on a single RF carrier.

IBOC has introduced new data services that expand the range of broadcaster functions and applications. Digital audio appears to the system as a source of data that may be traded off against data capacity to optimize both. Because of this, it permits synergistic cooperation between the audio and data services to:

– Permit the trade-off of digital audio fidelity (via bit rate adjustment) against data capacity
– Permit the trade-off of analogue audio fidelity (via bandwidth adjustment) against data capacity
– Provide additional opportunistic variable data capacity based on audio activity
– Provide various levels of data service quality (via adjustable error protection coding).

The IBOC system exhibits defined audio fidelity and robustness levels and provides resistance to multipath, Doppler, adjacent channel, grounded conductive structures, and impulse noise interference. It meets or exceeds the coverage of existing analogue audio and exhibits graceful audio degradation as signal strength diminishes.

2.2 Compatibility with existing analogue FM services

IBOC broadcasting represents a significant departure in the way future broadcasting equipment and receivers are built and function. HD Radio was introduced to the consumer and broadcasters gradually, in a way that did not immediately obsolete the current radio broadcast infrastructure (transmitters and receivers). The current population of radio receivers continue to work without modification until such time as analogue broadcasting is completely supplanted by the All-Digital mode. This was made possible by the initial introduction of Hybrid modes consisting of analogue signals augmented with digital signals.

Feature development is based on both transmitter and receiver functionality. Some broadcast systems may continue to operate entirely in the analogue environment while others are converted, in stages, from analogue, to hybrid, to the all-digital IBOC system. Flexibility in design and performance allow broadcasters to evolve seamlessly from analogue to hybrid to all-digital technologies.

IBOC broadcasting does not require new allocation of frequencies, and the over the air waveform will coexist within existing spectral emissions masks. The impact on existing analogue service is minimized. The IBOC system:

– Does not require a change in current protected contours.
– Minimizes interference to the analogue host in hybrid modes.
– Avoid harmful interference to co-channels and adjacent channels.
– Avoids harmful interference to, and remain compatible with, existing Subsidiary Communications Authorization (SCA) services in hybrid modes.
– Is compatible with the existing Emergency Alert System (EAS).
– Does not require changes to existing analogue radiated power in hybrid modes.

– Is compatible with existing radio frequency translators and boosters, as permitted in the United States.

– Minimizes the interference to co-channels and adjacent channels on the digital signals, in both hybrid and all-digital modes.

– Supports fast acquisition time at IBOC receivers, and

– Does not impair acquisition time of existing analogue receivers.

2.3 Use of on-channel repeaters for FM systems

The use of OFDM modulation in the VHF IBOC system allows on-channel digital repeaters to fill areas of desired coverage where signal losses due to terrain and/or shadowing are severe. A typical application occurs where mountains or other terrain obstructions within the station service areas limit analogue or digital performance. Specifics are discussed in § 3.6.

2.4 Seamless Transition from Analogue to Hybrid to All-Digital Systems

The introduction of IBOC Technology has been incremental and evolutionary in nature. Market and regulatory forces will necessitate evolutionary changes to the system. Such changes will in general conform to the following principles, to make changes as seamless as possible:

Analogue sunset (mandatory elimination of analogue broadcasting modes) is not required. The system exhibits forward and backward compatibility, supporting future audio CODEC enhancements while maintaining audio compatibility with earlier receivers.

The system exhibits forward and backward data compatibility, supporting future data service enhancements while maintaining earlier receivers' compatibility.

The system allows each broadcaster and consumer to upgrade according to their individual needs. From the beginning, IBOC receivers provided analogue, hybrid, and all-digital functionality, to remain useful throughout the entire evolution of the broadcasting industry.

IBOC technology provides a migration path for existing FM subcarrier SCA services when their host stations transition to an all-digital service.

As the system evolves, it will maximize use of existing electromagnetic spectrum as services move to new multicast and data services.

2.5 Economical implementation

The IBOC system features a wide variety of options, not all of which will be of interest to all broadcasters, all users or to all situations. Some features will interest travellers or mobile users but will be of little interest in the home or place of business, and vice versa. For that reason, manufacturers will offer specialty broadcast systems configured to offer just the right services for the various user situations or applications. That concept allows IBOC broadcast system manufacturers to produce designs that fit the needs of a broad range of users at a lower price point.

Conversion to IBOC transmission is affordable. It is cost effective because it:

– Minimizes new infrastructure requirements.

– Maximizes existing broadcaster infrastructure investment.

3 IBOC broadcast architecture

3.1 Studio considerations

Advancements in digital studio equipment have greatly improved the quality of audio that radio stations can reproduce. MW and VHF IBOC digital radio offers broadcasters the opportunity to capitalize fully on these improvements by transmitting digital information directly to a listener's receiver. However, IBOC broadcasts are only as good as the audio that is fed into the system. IBOC system will not be able to overcome any noise or audio impairment introduced before transmission. Studios wired without attention to good engineering practice are likely to have noise and crosstalk issues that may impact audio quality.

Digital programme source material that is bit reduced (digitally compressed) may degrade across multiple compression platforms. If high levels of bit reduction are employed, the likelihood of system degradation will increase. Some hard-disk music storage and retrieval systems use some form of low-loss digital compression. If incompatible digital audio storage components are integrated with the air chain elements, quality issues may arise. With digital storage costs rapidly decreasing, revisiting the audio storage methods employed at the studio is advisable. In general, bit reduction should be avoided unless required by cost or technical limitations. If bit reduction is used, it is suggested that one stays within the family of coding products to reduce the severity and frequency of trans-coding effects caused by multi-layer coding. Programme content also influences the degree to which compression impacts audio quality. Some formats will be more forgiving with higher levels of bit reduction than will others. In short, digital compression should be used cautiously.

Another issue that relates to the studio is real-time, off-air monitoring of programme content. IBOC digital sound broadcasting employs several methods of error correction that introduce delays between the analogue and digital signal. This time diversity allows backup audio channels to be substituted gracefully (blending) if any information is lost in the digital component of the IBOC signal. Because this delay makes it impossible to monitor directly off the air, it will require a pre-delay (live studio feed) to the talent's studio monitor and headsets. It is also advisable to install an automated alarm, which monitors signal or programme loss.

3.2 Audio processing

The purpose of audio processing for FM is two-fold: to control levels within a predetermined range to maximize transmission compatibility and secondly, to introduce a 'signature' sound quality.

Dynamic range, as used in this discussion, may best be described as the ratio of the largest signal to the smallest signal in volts peak to peak, measured at a given single frequency. To transmit signals for IBOC, it is not necessary to implement the same amount of dynamic range limitation as in an analogue broadcast. Analogue broadcast requires strict modulation control to meet deviation limits established by the FCC and ITU. However, it is desirable to use a single audio processor with dual IBOC and Analogue AES output to drive the analogue and digital transmitter paths. These dual IBOC/Analogue processors maintain time alignment coherency which is critically important when a receiver switches from analogue to digital at acquisition and from digital to analogue during a signal blend at the loss of digital. While it may not be necessary to process the digital as heavily as the analogue, it is still desirable to match the dynamics of the programme density and frequency response between both analogue and digital to avoid discontinuity during blending.

In an analogue-to-digital conversion, there are 'hard' dynamic limits that relate to the limitations of a digital signal processor (DSP). When these limits are exceeded, unpredictable and, possibly, undesirable effects are produced. It is therefore advisable to employ some form of audio processing whenever an analogue-to-digital transfer will take place. This should entail both limiting to prevent exceeding the dynamic range capability of the processor and level control to maximize the signal to noise ratio. In the digital-to-analogue conversion process, the dynamic range of the system is set by the resolution (number of bits) of the digital-to-analogue (D/A) converter. In this transfer mode, the dynamic range of the digital system will not exceed that of the analogue system as long as the absolute peak levels are set equally.

In a digital-to-digital exchange, such as when an AES/EBU interface is used, it is impossible to exceed the upper dynamic range limit of the device (i.e. clipping). The absolute dynamic range is limited by the respective resolutions of the source and object of the transfer. While it is impossible to overdrive the upper limit of the dynamic range, it is possible to under-drive and therefore not fully utilize the dynamic range of the system.

Because the digital domain has absolute limits and the analogue domain has variable limits, the audio transfer function is critical. Extreme care should be taken to employ limiting and level control when feeding audio from an analogue source to a digital system. If the dynamic range of the digital processor is exceeded, the audio will become extremely distorted as it exceeds these limits and produces ‘digital clipping’. As the signal is clipped, it will produce unwanted products within the desired audio band-pass. This is true of All-Digital processors when the entire dynamic range of the device has been exceeded.

Digital Signal Processors (DSPs) offer the broadcaster a vehicle to deliver repeatable audio performance with increased separation, audio definition and long-term stability. However, strict guidelines on interface of dissimilar systems must be adopted to take advantage of this performance. The goal of audio processing for IBOC is to introduce only as much dynamic range limitation as will be required to maintain audibility in an automotive environment. While the IBOC system is capable of reproducing nearly the complete dynamic range of the source material, it is not recommended, since a great deal of program content will be lost in the ambient noise level inside a car. Processing will always be a subjective issue and it is well outside the scope of this document to explain the ramifications of audio processing on time spent listening. Simply stated, it is desirable to offer the listener an improvement in fidelity in the transition to digital.

It is important to note that changing the amount of audio processing for the digital signal will not affect total modulation level or coverage. In general: it is best to use large signal levels without clipping to optimize signal-to-noise. In addition to input and output gain of the audio processor, possible adjustments include level into the exciter, level out of the exciter, DC carrier level in the transmitter (if used), and audio gain in the transmitter.

3.3 Studio-to-transmitter link

If audio processing will be performed at the transmitter site, a common studio-to-transmitter link (STL) system may be employed. With this option, one signal may be fed to the two independent audio processing chains: one for the IBOC signal's digital component and one for the analogue component. If audio processing will be performed at the studio, it may be desirable to add to the STL capacity. In this case, two discrete audio paths – one for the IBOC digital component of the signal and one for analogue component – could be transported to the transmitter site.

A fundamental consideration in the broadcast facility is whether the STL will be a linear or compressed system. While the goal is to be as linear as possible, this is often impractical due to technical or budgetary constraints.

As discussed in the section on studio equipment, the usage of bit reduction must be carefully monitored. Recent trends in STL development have centered on reducing the bandwidth requirements of both RF and IP and Telco based digital STL systems. In the case of RF based systems, this was to facilitate a digital stereo program feed within the limited spectrum of the FCC licensed auxiliary service channel. Bandwidth optimization has also been employed on Telco based systems to allow usage of lower cost, lower capacity data service lines. Stations that employ compressed STL channels are at greater risk for artifacts caused by compression.

If the STL employs compression, then the facility manager must also be concerned with the placement of audio processing. Perceptual coding techniques rely upon dynamic models as they relate to audio metrics. Undesirable anomalies may occur in the decoded audio if critical harmonic relationships are disturbed in the source audio fed to the coder.

3.4 IBOC VHF transmitters

Two methodologies exist for producing an IBOC Hybrid FM signal:

– Low-Level Combined/Commonly Amplified

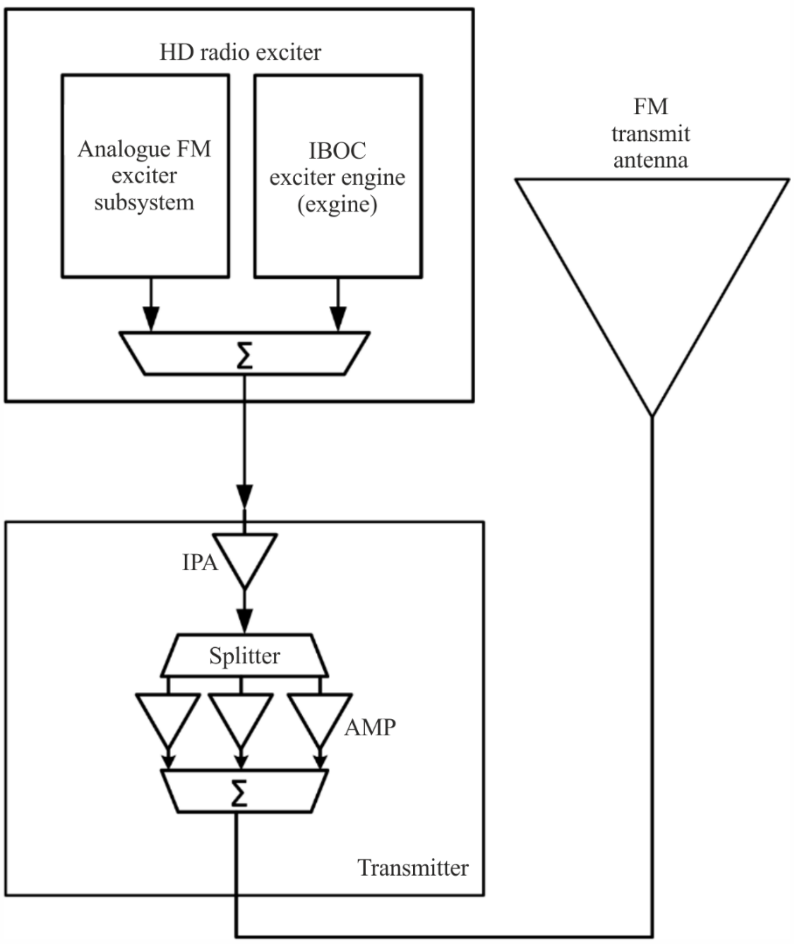
– High-Level Combined/Separately Amplified

3.4.1 Low-level combined/commonly amplified

The preferred approach is the 'low-level combined/commonly amplified' as depicted in Fig. 1. In this implementation, the low-level RF output of an analogue FM exciter is combined with the output of an IBOC digital exciter. The combined Hybrid output is fed to an intermediate power amplifier (IPA), split to multiple broadband amplifiers and combined to the desired Transmitter Power Output (TPO). This method reduces the number of independent elements in the broadcast chain and is typically the most space and power efficient.

FIGURE 1

Low-level combined



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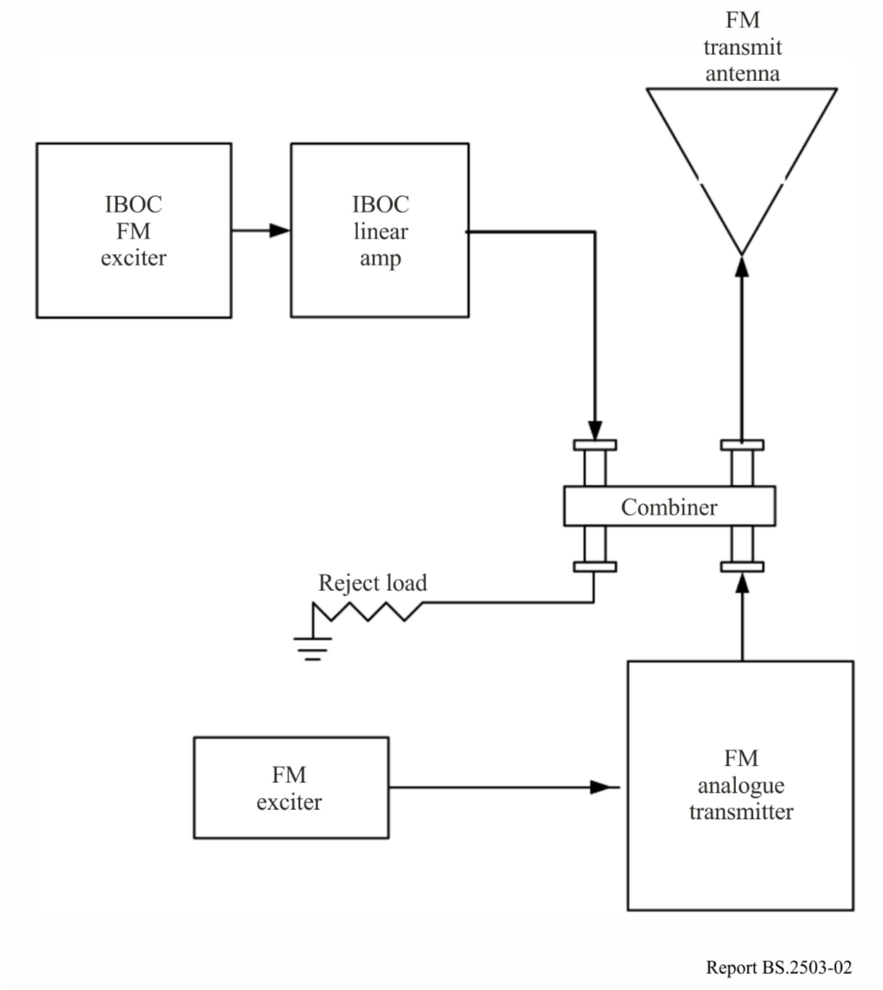
3.4.2 High-level combined/separately amplified

When IBOC broadcasting was first introduced, initial station conversions were accomplished using the second methodology, 'High-Level Combined/Separately Amplified', shown in Fig. 2. Separate amplification uses one of three methods to combine the analogue and digital signals.

FIGURE 2

High-level combined



With separate amplification, the analogue and digital signals may be combined in free space through separate purpose-built antennas, dual-input antennas or with a coupler combiner. Each of these methods have trade-offs and limitations.

3.4.3 10-dB coupler

Using a 10 dB coupler, the existing analogue station transmitter has its analogue RF output combined with the output of a separate digital transmitter compatible with IBOC Technology. The resulting hybrid signal is then be fed to the existing station antenna system. In the high-level combining method, power loss occurs due to power differences of the combined signal. These 10 dB coupler combiners result in a loss of about 0.5 dB (10%) of analogue power and 10 dB (90%) of digital power. When stations were operating at the initial authorized digital power of −20 dBc (1% of analogue power), this loss was tolerable. For example, in the case of an FM station with an analogue TPO of 10 kW, the digital carrier power of the IBOC signal would be 100 Watts. Assuming a coupler loss as given above, the analogue transmitter would need to be increased to 11.1 kW to overcome the coupler insertion loss. The digital transmitter will have to output an average power of 1kW to overcome the 10 dB combiner loss. The digital transmitter will also need to be sized to accommodate 5.5 dB of additional overhead for PAR. This sizing for peak will amount to three to four times the average power. When the FCC's digital power authorizations levels were increased unilaterally to −14 dBc the combiner losses rose to levels that were unacceptable and this method of combining fell out of favor.

3.4.4 Separate Analogue and Digital Antennas

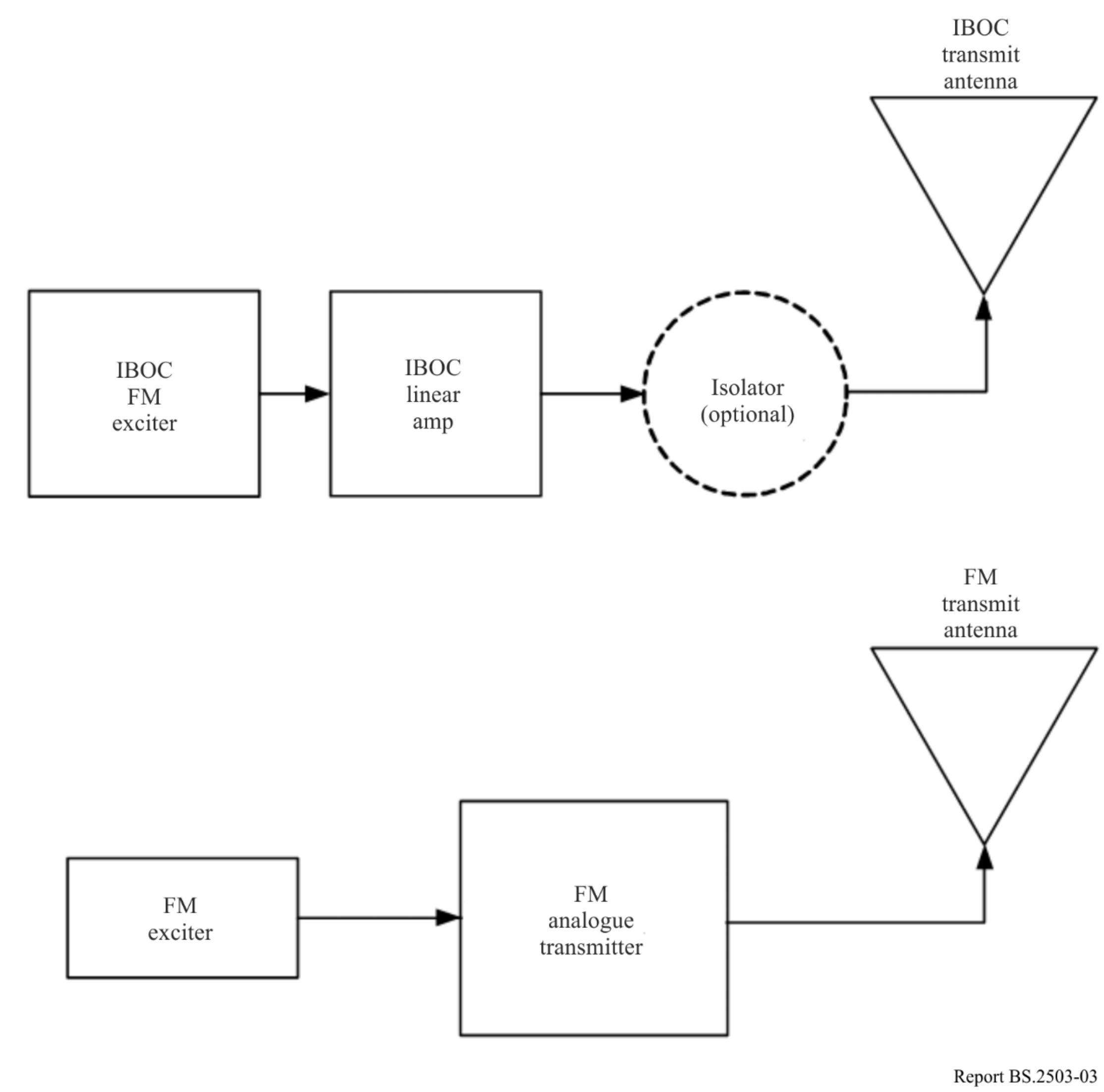
A separate antenna implementation is a method where an IBOC signal is transmitted from a licensed auxiliary (independent antenna from the analogue). The separate antenna methodology greatly reduced implementation costs and increased operating efficiency. It allowed stations that already had auxiliary antenna to quickly get their digital signal on-air. However, convenience comes at a price. Unless the antenna has identical radiating characteristics, and identical antenna mount placement, the pattern variances between the main analogue and digital auxiliary antenna create opportunity for the digital power ratio to be at variance from those authorized. If the digital power ratio is above that which is authorized, the probability for host analogue interference becomes statically significant. If the ratio is lower than those authorized the digital performance suffers. Broadcasters seeking to use separate antennas must provide the following information to ensure adequate digital performance and minimize the possibility of creating host analogue interference:

– The digital transmission must use a licensed auxiliary antenna.
– The auxiliary antenna must be within three seconds of latitude and longitude of the main antenna.
– The height above average terrain of the auxiliary antennas must be between 70 and 100 percent of the height above average terrain of the main antenna.
– dBmain isolation shall be greater than 46 dB.
– dBoutput isolation shall be greater than 40 dB.

To achieve this level of isolation requires careful placement and measurement of the antenna elements and may require additional methods to increase isolation.

FIGURE 3

Separate antenna configuration



The output of a High-Power Amplifier (HPA) must be isolated from extraneous, non-coherent signals. Insufficient isolation (too much extraneous energy back fed into the HPA) will usually cause spurious responses to be generated. A typical isolation specification for the HPA is −50 dBc for the level of such signals and this is in order so that spurious responses remain constrained to the FCC-mandated emissions mask for FM broadcasters. The antenna isolation budget variance from the HPA requirement is due to an allowance for amplifier turn-around loss and transmission line attenuation. Regardless, the IBOC linear HPA must be isolated from the host analogue FM HPA and conversely, both must be isolated from other HPAs (in a multi-station configuration) and from signals being received by the antenna. The latter is a realistic possibility: for example, in the case of several high-power FM broadcasting antennas in proximity on the same tower. Often, circulators are used to effect isolation. Circulators are nonreciprocal devices that, because of implementation techniques, can be nonlinear. In most cases they can be avoided, if desired, by relying on directional coupler or hybrid isolation to effect isolation between IBOC and analogue HPAs and by relying on filters to effect isolation between the antenna and both HPAs.

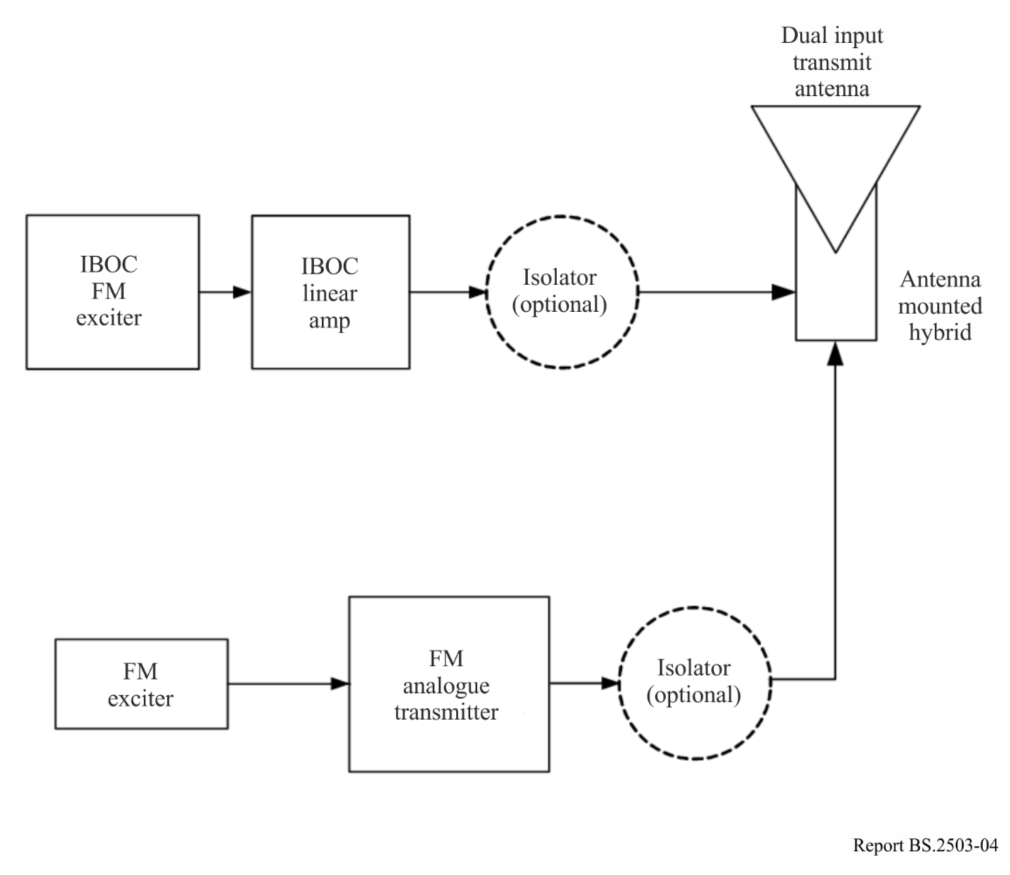
3.5 Dual input antenna

A dual Input antenna is another variation to use a high-level combined/separately amplified signal. In this implementation a purpose-built antenna is fed the analogue RF into one port of a hybrid which is attached directly to a panel or side-mount antenna bay. The analogue RF input generates right-hand circular polarization and the digital RF input is fed to other port generating left-hand circular polarization. Another variant of this design uses an array of antenna elements which alternate analogue and digital bays each fed by separate power dividers. Typically, this design also inverts the bay element to change the polarity reference to the analogue bay. This alternating polarity adds additional isolation between the analogue and digital signals. Analogue and digital signals are radiated from the same elements. The benefits of dual input antenna are:

– Low system insertion losses for both analogue and digital
– Up to 40 dB isolation between analogue and digital inputs
– Equal digital and analogue gain
– Uses no additional aperture
– No additional wind loading

FIGURE 4

Dual-input antenna configuration



3.6 On-channel digital repeaters

The use of orthogonal frequency division multiplexing in the VHF IBOC system allows on-channel digital repeaters to fill areas of desired coverage where signal losses due to terrain and/or shadowing are severe. A typical application occurs where mountains or other terrain obstructions within the station service areas limit analogue or digital performance.

OFDM systems, such as IBOC Technology, maintain a guard interval before each data symbol to provide receive robustness. The 75-μs delay used by the IBOC system not only contributes to this stability in normal multipath interference, but also allows for significant delay variability from multiple transmitters in an SFN overlap environment. In practice, the maximum permissible delay spread has been shown to be less than 65 μs (19.5 km) with field strength differentials less than 4 dB.

Field intensity ratios greater than four dB generally can be mitigated by the receiver's capture effect. This means that in a typical synchronized IBOC Digital SFN implementation, the boosted IBOC signal (unlike analogue) will rarely experience destructive interference in the overlap zone.

To avoid significant inter-symbol interference the effective coverage in the direction of the primary transmission system should be limited to within 22 km. Specifically, the ratio of the signal from the main transmitter to the booster signal should be at least 10 dB at locations more than 22 km from the repeater in the direction of the main antenna. Performance and distances between on-channel boosters can be improved using directional antennas to protect the main station. The coverage in the direction pointing away from the primary antenna can be arbitrarily large but must conform to the FCC coverage allocation for that station.

3.7 FM subsidiary communications authorization compatibility

The IBOC broadcast system enables a variety of enhanced data services delivered by radio. The IBOC Hybrid mode has shown compatibility with FM subcarriers below 92 kHz, including RDS. SCA performance is dictated by the SCA receiver filter design. Typically, the impact to 92 kHz operation is negligible and may be resolved with minor modification.

4 Broadcast system functional types

Implementation of an IBOC broadcasting system is accomplished by one of the following strategies:

– Systems converted from analogue-only operation.

– Systems designed and constructed from the outset to be IBOC compliant.

It is anticipated that most systems will follow the first (conversion from analogue) strategy. IBOC broadcasting systems, however implemented, will be of the following defined types.

4.1 Operational hybrid types

Hybrid IBOC broadcasting systems will transmit an analogue carrier signal which is compatible with existing analogue radio receivers and will be identical to the analogue carrier signal of existing analogue only systems, augmented with digital sidebands which carry digital audio and data, in the manner prescribed herein.

4.2 Operational all-digital types

All-Digital IBOC broadcasting systems have been developed for future applications. The analogue carrier portion of the broadcast signal will be removed, and secondary digital subcarriers utilized in the manner prescribed herein. The primary subcarriers are identical to those of Hybrid systems and support a fast-acquisition service to enable a better user experience when tuning to the digital-only broadcast.

4.3 Reference broadcast system

Reference IBOC broadcasting systems have been designed as both Hybrid and All-Digital compatible and will comply with all specifications of the IBOC system. The purpose of reference IBOC broadcasting systems is as follows:

– Performance testing for system development, and for receiver certification.

– Guidance for broadcast equipment developers.

4.4 IBOC data service channel

The IBOC data service (IDS) channel is a fixed rate channel that delivers basic control messages.

Basic control messages carry service information. Service information is additional information about the services carried in real time, other information such as schedules or service event calendars, and station related system broadcast information like existing RDS services.

4.5 Datacasting system

Datacasting is defined as delivering content from a content provider to a receiver end user via the IBOC system. Datacasting affords expanded data functions over those provided by the IDS channels. These include, but are not limited to, the following:

– Streaming perceptual audio CODEC (HDC) applications.
– Still and streaming video applications.
– Message/packet-based applications.
– File based applications.
– Audio storage and retrieval applications.
– Billing and management.
– Text/XML (Extended Markup Language) applications.
– Specialized applications with specialized receivers.
– Datacasting services with various defined levels of quality of service for each.
– Control data beyond that provided by the IDS channel.

IBOC system datacasting users are of three types:

– Content providers who create and package content for broadcast over the IBOC system.
– Operations, administrative, and maintenance (OAM) users who manage the broadcast system for content delivery, and billing and other administrative tasks support.
– Receiver end users who consume the content broadcast by the IBOC system.

The IBOC system interfaces with content providers to receive content data for broadcast, with the receiver system (via the air interface) to deliver the content, and with OAM users to administer and maintain the datacasting service.

For purposes of datacasting definition and specification, the IBOC broadcasting system consists of two parts:

– Broadcast network system that receives content from content providers and delivers it to individual broadcast station systems.
– Broadcast station systems that receive content from the broadcast network system, or from local content providers, for broadcast.

4.6 Emergency alert system

The Emergency alert system (EAS) is an existing government mandated service that is maintained in the IBOC Hybrid broadcasting system. The Hybrid systems are compatible with the existing EAS by means of the existing main analogue carrier signal. The All-Digital system also provides a functional equivalent and enhancement to the EAS system.

4.7 GPS synchronization

In order to ensure precise time synchronization, the transmitted signal for each station may be GPS synchronized.

This is normally accomplished through synchronization with a signal synchronized in time and frequency to the Global Positioning System (GPS)[1]. In the case where transmissions are not locked to GPS, time and frequency synchronization[2] the accuracy requirements are relaxed, and transmissions cannot be synchronized with other stations.

4.8 RF carrier frequency and OFDM symbol clock

For synchronization Level I transmission facilities, the absolute accuracy of the carrier frequency and OFDM symbol clock frequency will be maintained.

For synchronization Level II transmission facilities, the absolute accuracy of the carrier frequency and OFDM symbol clock frequency will be maintained.

4.9 GPS phase lock

For Level I transmission facilities, all transmissions will maintain phase lock to absolute GPS time. If the above specification in a synchronization Level I transmission facility is violated due to a GPS outage or other occurrence, it will be classified as a synchronization Level II transmission facility until the above specification is again met.

5 FM IBOC RF requirements

The requirements for the spectral emissions limits for the hybrid transmissions and the all-digital transmissions are given in §§ 0 and 0.

The spectral requirements and emissions limits presented in this Report reflect the emissions requirements of U.S. Federal Communications Commission, ITU Recommendations and the transmission mask to minimize interference between co-channel and adjacent channel transmissions. Additional technical requirements to provide reliable digital carrier acquisition and tracking are incorporated into the emissions limits.

The emissions limits and broadcast mask are further defined in NRSC-5-D (reference [3]) and Recommendation ITU-R BS.1660-8.

5.1 FM hybrid and extended hybrid digital carrier power

5.1.1 Hybrid and extended hybrid system carrier configuration

Hybrid transmission utilizes two OFDM subcarrier sets (sidebands) located up to 198 kHz above and below the analogue carrier center frequency. The basic Hybrid (MP1) service mode uses 191 subcarriers per sideband beginning in frequency at approximately ±129 kHz from the center frequency. Extended Hybrid service modes MP2, MP3, and MP11 add additional subcarriers closer to the analogue carrier, with MP11's subcarriers starting at approximately ±101 kHz.

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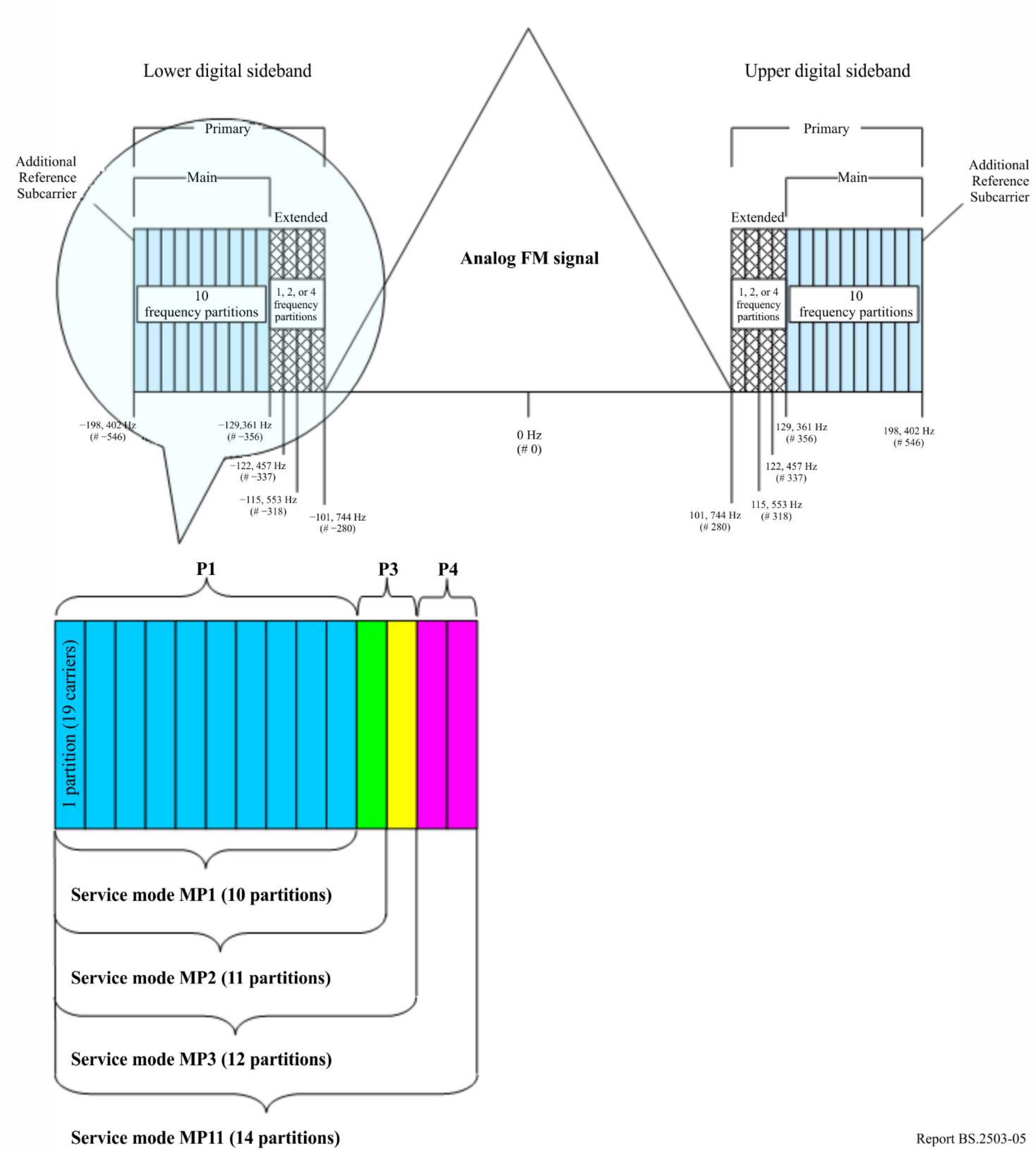
[1] GPS Locked stations are referred to as Level 1: GPS-locked transmission facilities.

[2] Level I: Non-GPS locked transmission facilities.

FIGURE 5

Extended hybrid waveform – Sideband detail



As shown in Fig. 5, each frequency partition consists of 19 subcarriers (except for two extra reference subcarriers at the limits of the primary main partitions). In the lower digital sideband, Fig. 5 also details each of the sideband groups for each Hybrid service mode. The power of each subcarrier is set at −45.8 dBc (dB below the reference analogue carrier) for a −20 dBc total integrated digital to analogue power ratio in service mode MP1.

TABLE 1 characterizes power at other digital-to-analogue power ratios in the four FM Hybrid service modes. Since the absolute power of the subcarriers is additive, if 10 subcarrier groups make up the MP1 reference power level, one more group will increase the power by 10% and so on. Note that there is one extra reference subcarrier in each of the primary main sidebands, skewing the power calculation slightly. This amounts to approximately 0.4% of the total power in the MP3 mode or 0.02 dB, which is considered negligible.

5.2 Digital power for hybrid mode at various digital to analogue power ratios

TABLE 1 characterizes the total integrated digital power and single sideband power for the four Hybrid service modes and various digital to analogue power ratios. The nominal digital-to-analogue power ratio is derived assuming a digital-to-analogue power ratio of −20 dBc. Other power ratios are scaled appropriately as referenced in TABLE 1.

TABLE 1

Sideband power for various service modes and digital to analogue power ratios

Nominal digital-to-analogue power ratio (dBc) service mode MP1	Single subcarrier power (dBc)	Total integrated power of both sidebands (dBc)				Total integrated power of one sideband (dBc)			
		MP1 100% of MP1 power	MP2 110% of MP1 power	MP3 120% of MP1 power	MP11 140% of MP1 power	MP1 100% of MP1 power	MP2 110% of MP1 power	MP3 120% of MP1 power	MP11 140% of MP1 power
−20.0	−45.8	−20.0	−19.6	−19.2	−18.5	−23.0	−22.6	−22.2	−21.5
−14.0	−39.8	−14.0	−13.6	−13.2	−12.5	−17.0	−16.6	−16.2	−15.5
−13.0	−38.8	−13.0	−12.6	−12.2	−11.5	−16.0	−15.6	−15.2	−14.5
−12.0	−37.8	−12.0	−11.6	−11.2	−10.5	−15.0	−14.6	−14.2	−13.5
−11.0	−36.8	−11.0	−10.6	−10.2	−9.5	−14.0	−13.6	−13.2	−12.5
−10.0	−35.8	−10.0	−9.6	−9.2	−8.5	−13.0	−12.6	−12.2	−11.5

5.3 Power limits for asymmetrical sideband operation

If asymmetrical sideband operation is desired, the lower and upper digital sidebands are considered separately and the single sideband power values in TABLE 3TABLE 1 are used. Note that these values are simply three dB less than the corresponding total integrated power for both sidebands. If broadcasting in MP3 mode, for example, setting the lower sideband at −10 dBc and the upper at −14 dBc will result in a total integrated power of:

$$= 10 \log_{10} (\log_{10}{}^{-1} (\text{Pwr1} /10) + \log_{10}{}^{-1} (\text{Pwr2} /10))$$

$$= 10 \log_{10} (\log_{10}{}^{-1} (-12.2 /10) + \log^{10\ -1} (-16.2 /10))$$

$$= 10 \log_{10} (0.060 + 0.024)$$

$$= 10 \log_{10} (0.084)$$

$$= -10.8 \text{ dBc}$$

Note that the total integrated power is dominated by the highest-powered sideband.

5.4 Spectral emissions limits for hybrid transmissions

For hybrid transmissions, measurements of the combined analogue and digital signals shall be made by averaging the power spectral density of the signal in a 1 kHz bandwidth over a minimum time span of 30 seconds and a minimum of 100 sweeps. Compliance will be determined by measuring the composite power spectral density of the analogue and digital waveforms. The measurement point and the test configuration shall be as described in Subsection 4.2 of Reference [2].

Zero dBc is defined as the total power of the analogue FM carrier.

Under normal operation with analogue modulation present, the following requirements shall be met at all times:

– Noise and spuriously generated signals from all sources, including phase noise and intermodulation products, shall conform to the limits as described in the following paragraph and shown in Fig. 6 and Table 2. These limits are applicable for all permissible power levels of the upper and lower sidebands, as defined in § 4.5.

– The measured power spectral density of the Hybrid analogue and digital signals at frequencies removed from the centre of the channel between 100 kHz and 200 kHz shall not exceed –30.0 dBc/kHz.

– The measured power spectral density of the Hybrid analogue and digital signals at frequencies removed from the center of the channel by 200 to 207.5 kHz shall not exceed [–30.0 – (|frequency in kHz| – 200 kHz) · 4.187] dBc/kHz.

– The measured power spectral density of the Hybrid analogue and digital signals at frequencies removed from the center of the channel by 207.5 to 250 kHz shall not exceed [–61.4 – (|frequency in kHz| – 207.5 kHz) · 0.306] dBc/kHz.

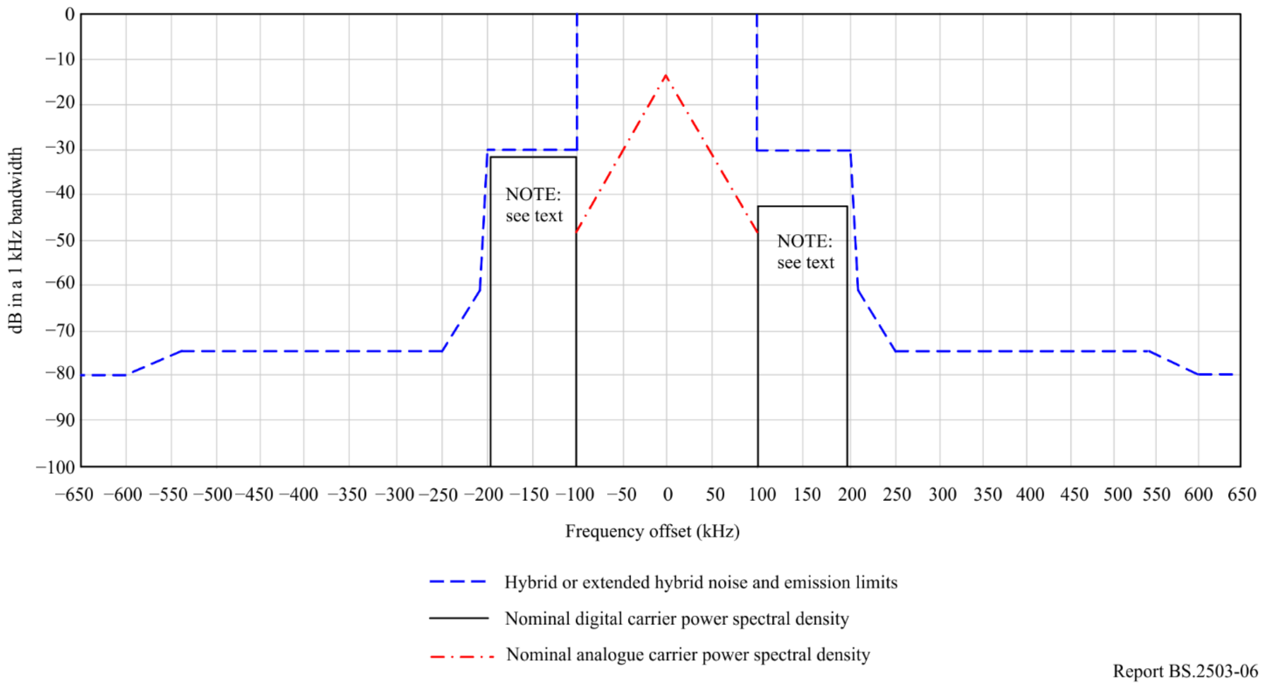
– The measured power spectral density of the hybrid analogue and digital signals at frequencies removed from the centre of the channel between 250 kHz and 540 kHz shall not exceed –74.4 dBc/kHz.

– The measured power spectral density at frequencies removed from the center of the channel by more than 540 to 600 kHz shall not exceed [–74.4 – (|frequency in kHz| – 540 kHz) · 0.093] dBc/ kHz.

– The measured power spectral density at frequencies greater than 600 kHz from the centre of the channel shall not exceed –80.0 dBc/kHz.

FIGURE 6

IBOC VHF hybrid waveform noise and emissions limits



NOTE – The upper and lower sidebands may differ in power level by up to 10 dB (asymmetric sidebands). Normally, the sideband power levels are equal, but under certain scenarios, asymmetric sidebands may be useful for mitigation of adjacent channel interference. Figure 6 shows a power-level difference of 10 dB for purposes of illustration. It shall be noted that even though the upper and lower sidebands have different power levels, the upper and lower spectral emissions limits are the same.

TABLE 2

IBOC VHF hybrid waveform noise and emissions limits

Frequency offset relative to carrier	Level (dBc/kHz)
100 – 200 kHz offset	-30.0
200 – 207.5 kHz offset	[–30.0 – (|frequency in kHz| – 200 kHz) • 4.187]
207.5 – 250 kHz offset	[–61.4 – (|frequency in kHz| – 207.5 kHz) • 0.306]
250 – 540 kHz offset	–74.4
540 – 600 kHz offset	[–74.4 – (|frequency in kHz| – 540 kHz) • 0.093]
>600 kHz offset	–80.0

NOTE – The requirements for noise and spurious emission limits defined in this subsection reflect acceptable performance criteria. In certain circumstances, additional measures (filtering, active emissions suppression, etc.) may be needed to reduce the spectral emissions below the limits given in this subsection in order to reduce mutual interference between broadcast stations.

5.5 Spectral emissions limits for all-digital transmissions

For all-digital transmissions, measurements of the all-digital signal shall be made by averaging the power spectral density of the signal in a 1 kHz bandwidth over a minimum time span of 30 seconds and a minimum of 100 sweeps. The measurement point and the test configuration shall be as described in Subsection 4.2 of Reference [2].

Zero dBc is defined as the nominal power spectral density in a 1 kHz bandwidth of the digital primary main sidebands.

Under normal operation, the following requirements shall be met at all times:

– Noise and spuriously generated signals from all sources including phase noise and intermodulation products, shall conform to the limits as described in the following paragraph and as shown in Fig. 7 and Table 3.

– The measured power spectral density of the all-digital signal at frequencies removed from the centre of the channel by 200 to 207.5 kHz shall not exceed [–20 – (|frequency in kHz| – 200 kHz) · 1.733] dBc/kHz.

– The measured power spectral density at frequencies removed from the centre of the channel by more than 207.5 kHz to 250 kHz shall not exceed [–33 – (|frequency in kHz| – 207.5 kHz) · 0.2118] dBc/kHz.

– The measured power spectral density at frequencies removed from the centre of the channel by 250 to 300 kHz shall not exceed [–42 – (|frequency in kHz| – 250 kHz) · 0.56] dBc/kHz.

– The measured power spectral density at frequencies removed from the centre of the channel by more than 300 kHz and up to 600 kHz shall not exceed –70 dBc/kHz.

– Any emission appearing on a frequency removed from the centre of the channel by more than 600 kHz shall not exceed –80 dBc/kHz.

FIGURE 7

IBOC VHF all-digital waveform noise and emissions limits

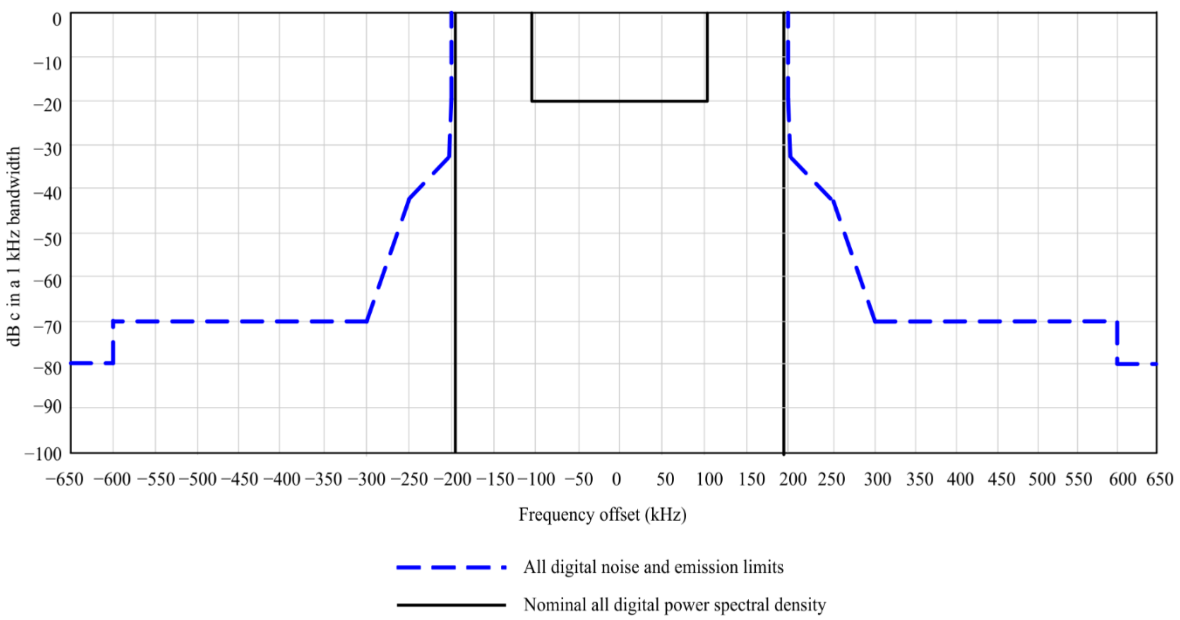


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TABLE 2

IBOC VHF all-digital waveform noise and emissions limits

Frequency offset relative to carrier	Level (dBc/kHz)
200 – 207.5 kHz offset	[–20 – (|frequency in kHz| – 200 kHz) • 1.733]
207.5 – 250 kHz offset	[–33 – (|frequency in kHz| – 207.5 kHz) • 0.2118]
250 – 300 kHz offset	[–42 – (|frequency in kHz| – 250 kHz) • 0.56]
300 – 600 kHz offset	–70
>600 kHz offset	–80

NOTE – The requirements for noise and spurious emission limits defined in this subsection reflect acceptable performance criteria. In certain circumstances, additional measures (filtering, active emissions suppression, etc.) may be needed to reduce the spectral emissions below the limits given in this subsection in order to reduce mutual interference between broadcast stations.

For all-digital transmissions, the region within 100 kHz from the centre channel shall be reserved for secondary low-level subcarriers.

5.6 Digital sideband levels

The amplitude scaling of each OFDM subcarrier within each digital sideband is given in TABLE 4 for the hybrid, extended hybrid, and all-digital waveforms. The values for the hybrid and extended hybrid waveforms are specified relative to the analogue FM power. A value of one (1) would produce a digital subcarrier power equal to the total power in the unmodulated analogue FM carrier. The values for the all-digital waveform are relative to total authorized digital power that is allocated to the broadcast facility.

For the hybrid and extended hybrid waveforms, the minimum values of a0U and a0L were chosen so that the total average power in a primary main digital sideband (upper or lower) is 23 dB below the total power in the unmodulated analogue FM carrier. The power of each primary sideband may be individually increased according to the maximum values shown in Table 4. Therefore, total average power in each primary main digital sideband (upper or lower) is subject to an upper limit of 13 dB below the total power in the unmodulated analogue FM carrier. Normally, the upper and lower sideband power levels are equal, but under certain scenarios, asymmetric sidebands may be useful for mitigation of adjacent channel interference.

For the all-digital waveform, the value of a1 was chosen so that the total average power of all the primary digital subcarriers combined is equal to one. The values for a2 through a5 were chosen so that the total average power in the secondary digital subcarriers (upper and lower) lies in the range of five to 20 dB below the total power in the All-Digital primary digital subcarriers.

TABLE 4

OFDM subcarrier scaling

Waveform	Service Mode	Sidebands	Amplitude scale factor notation	Power spectral density per subcarrier (dBc)		Power spectral density in a 1-kHz bandwidth (dBc)	
				Min	Max	Min	Max
Hybrid	MP1	Primary	a0L	−45.8	−35.8	−41.4	−31.4
			a0U	−45.8	−35.8	−41.4	−31.4
Extended Hybrid	MP2, MP3, MP11, MP5, MP6	Primary	a0L	−45.8	−35.8	−41.4	−31.4
			a0U	−45.8	−35.8	−41.4	−31.4
All-Digital	MP5, MP6	Primary	a1	−27.3		−22.9	
	MS1 – MS4	Secondary	a2	−32.3		−27.9	
		Secondary	a3	−37.3		−32.9	
		Secondary	a4	−42.3		−37.9	
		Secondary	a5	−47.3		−42.9	

5.7 RF spectral inversion

The RF spectrum of the digital waveform shall be inverted as compared to its baseband representation. This means that the lower sideband shall occupy the higher frequencies within the RF channel. And the upper sideband shall occupy the lower frequencies within the RF channel. Hence, scale factor a0L shall be used to set the power level of the higher frequency sideband and a0U shall be used to set the power level of the lower frequency sideband.

5.8 Phase noise

The phase noise mask for the broadcast system is illustrated in Figs 8 and 9 and specified in Table 5. As can be seen in the Figures, the response is linear (on the dB scale) between every pair of points drawn on the curve.

Phase noise is inclusive of all sources from the Exciter input to the antenna output as measured in a 1 Hz bandwidth.

Zero dBc is defined as the total power of the subcarrier being measured. The phase noise mask is applicable for all permissible power levels of the upper and lower sidebands, as defined in § 5.6.

The total single sideband phase noise of any digital subcarrier at the transmitter RF output as measured in a 1 Hz bandwidth shall be within the mask specified in Table 5. This shall be verified by transmitting a single unmodulated digital subcarrier. In addition, for the Hybrid waveform, the analogue FM carrier shall be disabled.

TABLE 3

FM broadcast system phase noise specification

Frequency offset relative to carrier (F)	Level (dBc/Hz)
10-100 Hz	–2.78×10-1 F – 39.2
100-1 000 Hz	–1.11×10-2 F – 65.9
1-10 kHz	–1.11×10-3 F – 75.9
10-100 kHz	–2.22×10-4 F – 84.8
> 100 kHz	–107.0

FIGURE 8

FM SSB phase noise mask | 10 Hz to 1 000 Hz

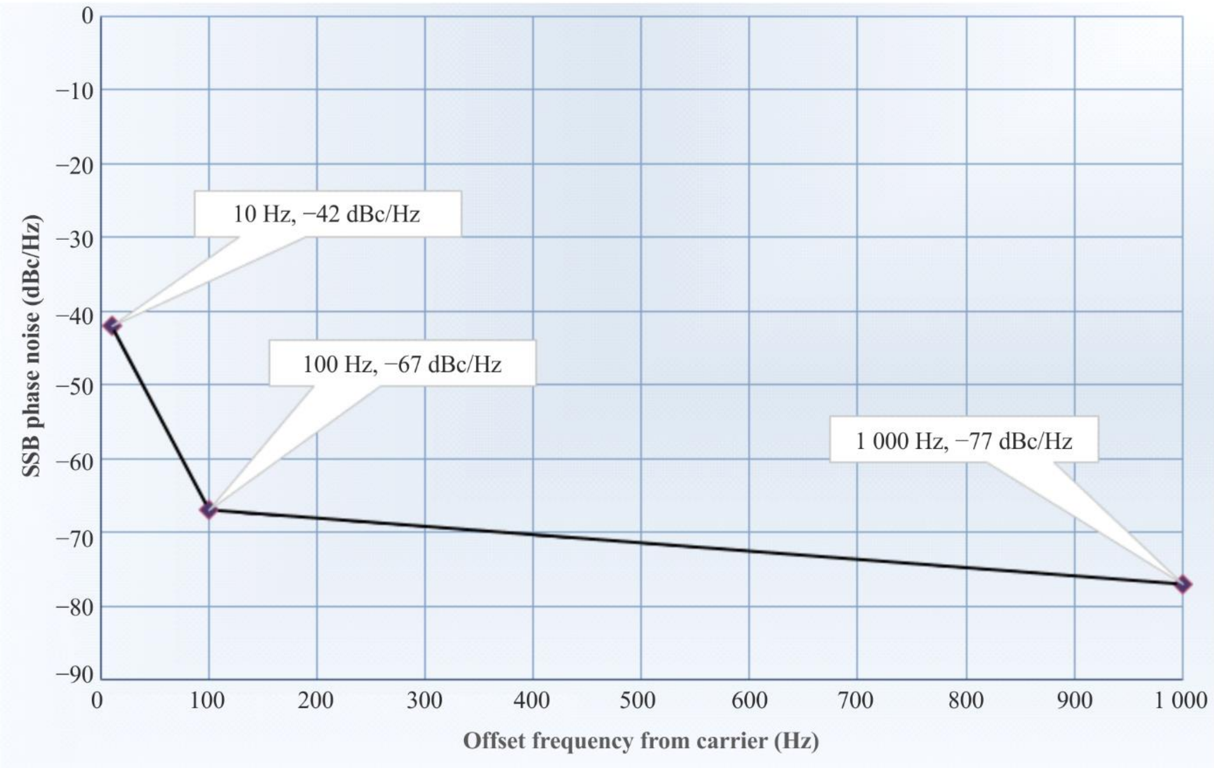

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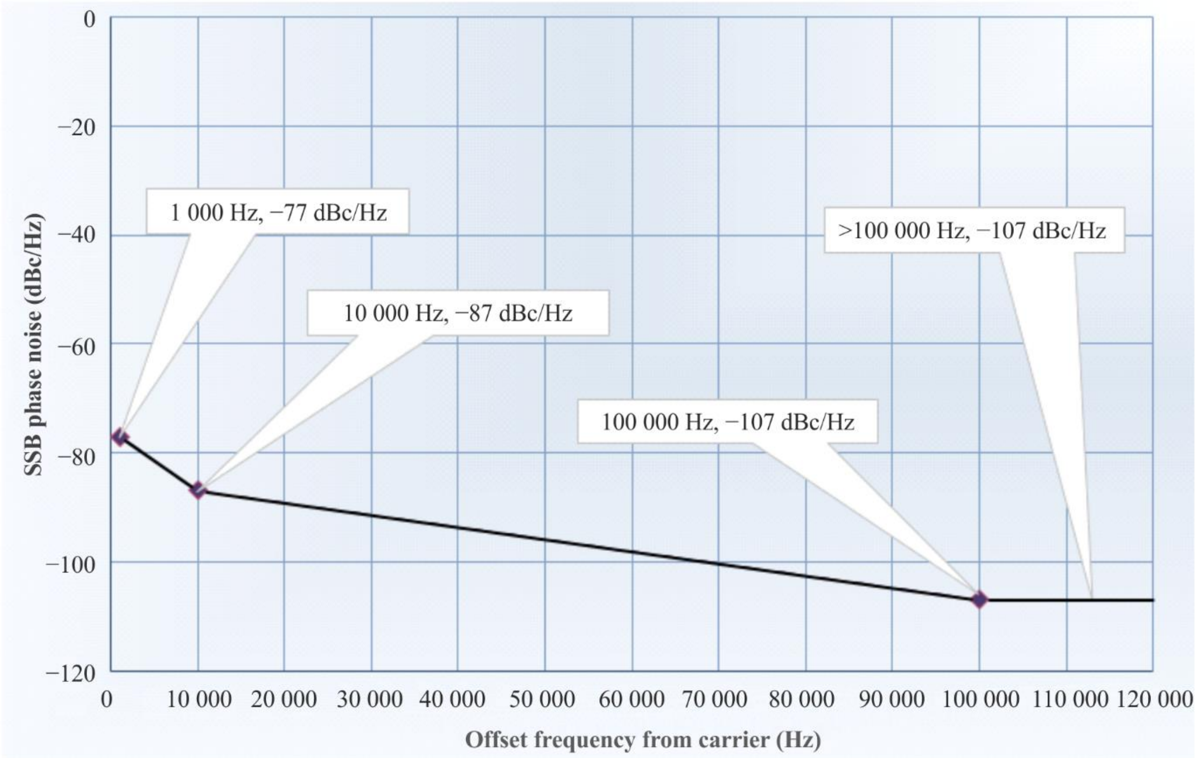
FIGURE 9

FM SSB phase noise mask | 1 kHz to 100 kHz



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5.9 Discrete phase noise

For the broadcast system, the spectrum from (Fc – 200 kHz) to (Fc + 200 kHz) shall be considered to consist of multiple non-overlapping sub-bands, each with a bandwidth of 300 Hz, where Fc is the carrier frequency. Discrete phase noise components measured at the transmitter RF output shall be permitted to exceed the mask specified in TABLE 3 provided that for each sub-band, the measured total integrated phase noise does not exceed the total integrated phase noise calculated from Table 5.

If the upper and lower sidebands have different power levels, as permitted in § 0, the measurement must account for the fact that the 0 dBc reference level will be different for each sideband.

5.10 Modulation error ratio

Modulation Error Ratio (MER) is a useful signal quality metric, quantifying the ratio of the rms noise of one or more subcarriers to the subcarrier nominal magnitude(s). Thus, it is a measure of the signal-to-noise ratio (in units of dB) of the broadcast signal, inclusive of both linear and non-linear distortions within the broadcast system itself. Refer to SY_TN_2646s [1] for details of how MER is measured and computed.

The following specifications shall be met using the test configuration described in subsection 6.2 of [2]. MER equations are provided in [1].

Reference Subcarriers

1) The MER for each and every Binary Phase Shift Keying (BPSK) reference subcarrier, measured at the RF output of the transmission system at the connection point to the antenna system (including any RF filters), shall be greater than or equal to 11 dB, as computed by Equation 1. The parameter *N* in Equation 1, the total number of contiguous symbols used in the average, shall be set to 128.

2) The average MER of all the BPSK reference subcarriers in the upper sideband, measured at the RF output of the transmission system at the connection point to the antenna system (including any RF filters), shall be greater than or equal to 14 dB, averaged across all upper reference subcarriers, as computed by Equation 2a. This computation shall be based on a block of $N = 128$ contiguous symbols.

3) The average MER of all the BPSK reference subcarriers in the lower sideband, measured at the RF output of the transmission system at the connection point to the antenna system (including any RF filters), shall be greater than or equal to 14 dB, averaged across all lower reference subcarriers, as computed by Equation 2b. This computation shall be based on a block of $N = 128$ contiguous symbols.

5.10.1 Data subcarriers

1) The MER for each and every Quadrature Phase Shift Keying (QPSK) data subcarrier partition in the lower sideband, measured at the RF output of the transmission system at the connection point to the antenna system (including any RF filters), shall be greater than or equal to 11 dB, as computed by Equation 4a. The parameter N in Equation 4a, the total number of contiguous symbols used in the average, shall be set to 128.

2) The MER for each and every QPSK data subcarrier partition in the upper sideband, measured at the RF output of the transmission system at the connection point to the antenna system (including any RF filters), shall be greater than or equal to 11 dB, as computed by Equation 4b. The parameter N in Equation 4b (the total number of contiguous symbols used in the average) shall be set to 128.

3) The average MER of all the QPSK data subcarriers in the upper sideband, measured at the RF output of the transmission system at the connection point to the antenna system (including any RF filters), shall be greater than or equal to 14 dB, averaged across all upper data subcarrier partitions, as computed by Equation 5a. This computation shall be based on a block of $N = 128$ contiguous symbols.

4) The average MER of all the QPSK data subcarriers in the lower sideband, measured at the RF output of the transmission system at the connection point to the antenna system (including any RF filters), shall be greater than or equal to 14 dB, averaged across all lower data subcarrier partitions, as computed by Equation 5b. This computation shall be based on a block of $N = 128$ contiguous symbols.

5.10.2 Data subcarrier to reference subcarrier power ratio

In addition to the gain flatness specifications stated in § 0, the ratio of the average data subcarrier power to the average reference subcarrier power, as computed by Equations 3a and 3b in [1], shall comply with the following limits:

$$-0.5 \le RdB_{upper} \le 1.0 \text{ dB}$$

$$-0.5 \le RdB_{lower} \le 1.0 \text{ dB}$$

5.11 Gain flatness

The total gain of the transmission signal path as verified at the antenna output shall be flat to within ±0.5 dB for all frequencies between (Fc – 200 kHz) to (Fc + 200 kHz), where Fc is the RF channel frequency. It is assumed that the source data consists of scrambled binary ones and the power of each subcarrier is an average value.

For the case where the upper and lower digital sideband power levels are intended to be different, as defined in § 0, the gain flatness specification shall be interpreted as follows:

Gain flatness is the difference between the measured power spectral density in a 1-kHz bandwidth of each subcarrier frequency, and the power spectral density of the applicable digital primary main sideband, normalized to a 1 kHz bandwidth.

For optimal IBOC digital performance, it is recommended that the transmission system, including the antenna, adheres as closely as is practicable to the gain flatness specification. Performance may be verified using a suitable sample loop on the reference or main tower. In addition to antenna component selection and adjustment, active pre-compensation of the IBOC waveform may be employed to improve the effective gain flatness.

5.11.1 Group delay flatness

The differential group delay variation of the entire transmission signal path (excluding the RF channel) as measured at the RF channel frequency (Fc) shall be within 600 ns peak to peak from (Fc – 200 kHz) to (Fc + 200 kHz).

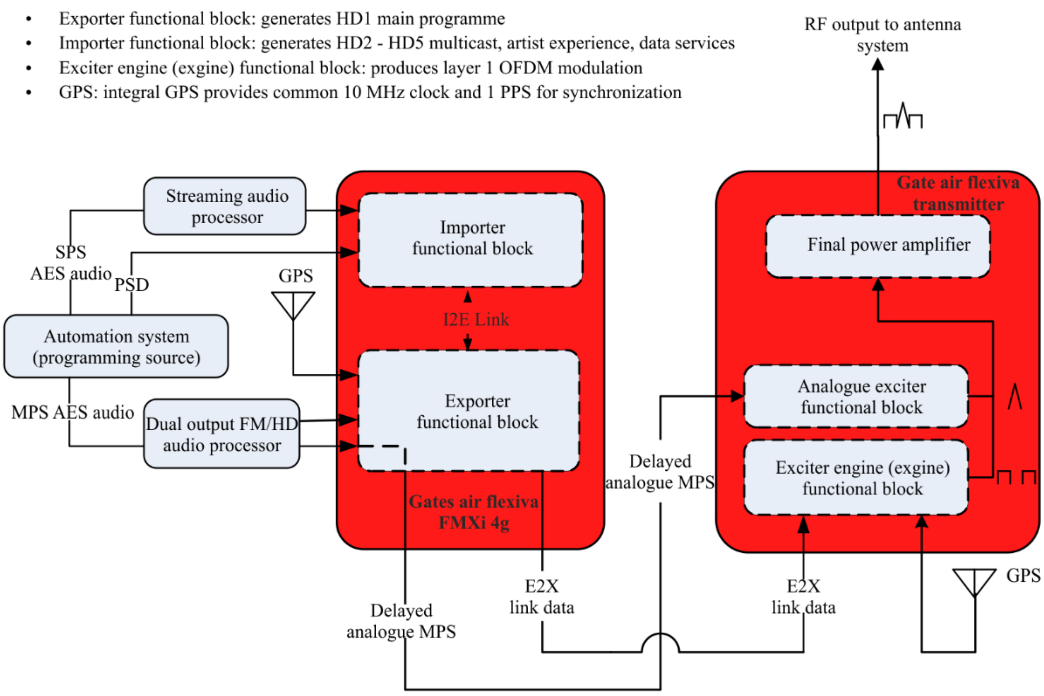
6 IBOC broadcast topology

The following sections provide examples of broadcast topology for several transmission equipment manufacturers. Each follows the same basic architecture. However, some internal functional blocks differ based on manufacturer implementation. Regardless, each broadcast solution meets the IBOC transmission requirements outlined in NRSC-5-D.

6.1 Gates air broadcast topology

FIGURE 10

Gates air broadcast topology



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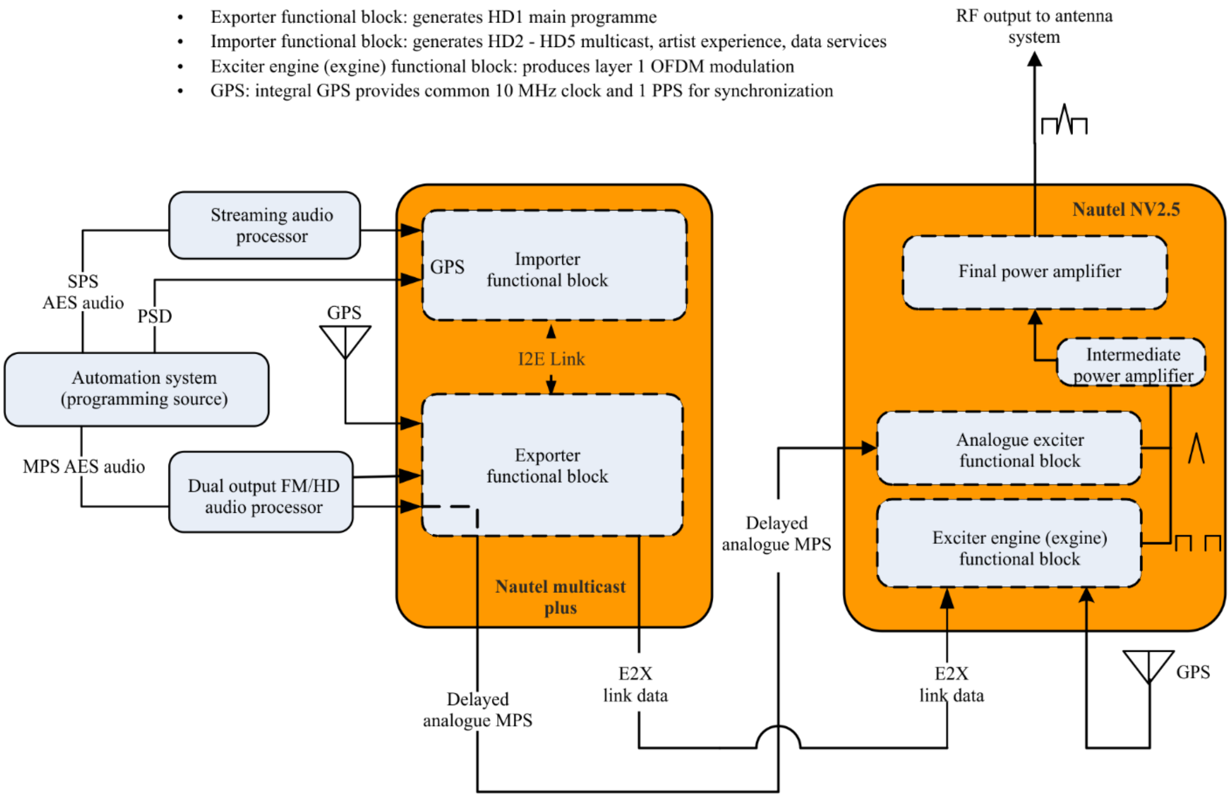
6.2 Nautel broadcast topology

FIGURE 11

Nautel broadcast topology



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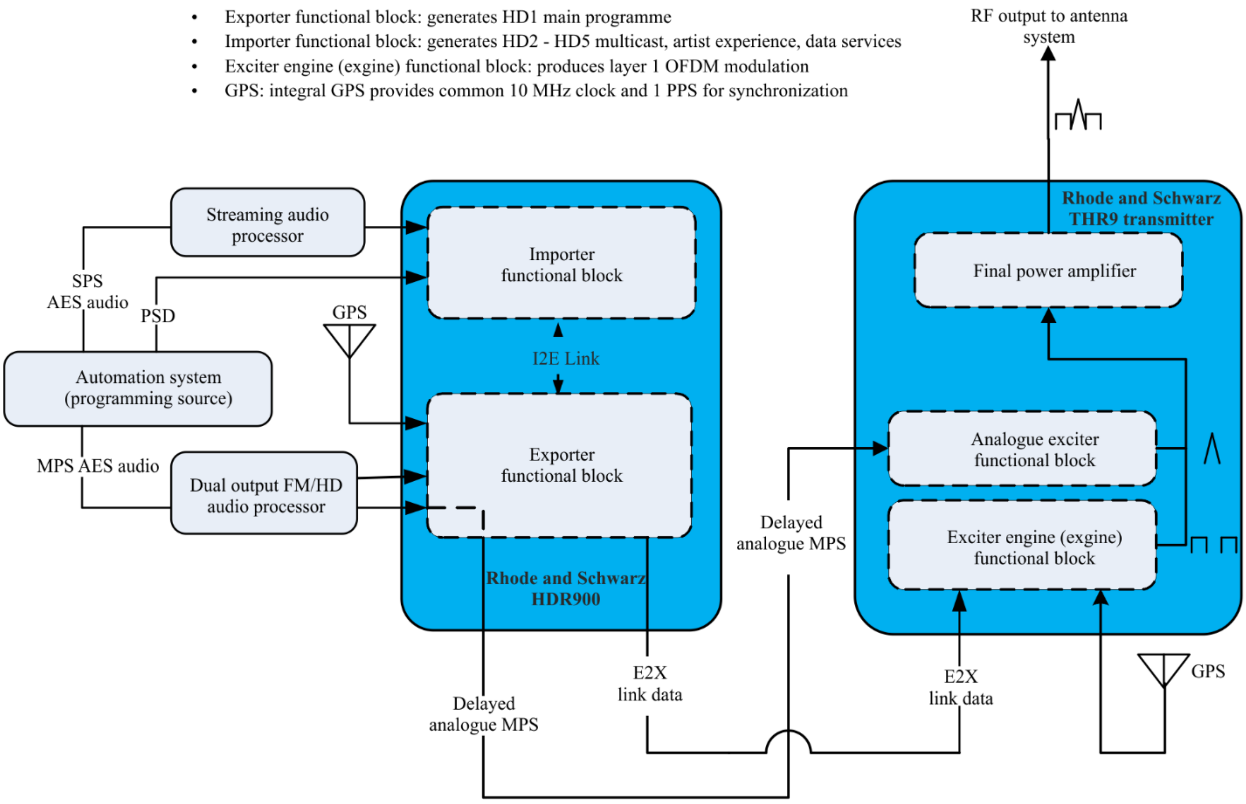
6.3 Rohde & Schwarz broadcast topology

FIGURE 12

Rohde & Schwarz broadcast topology



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7 Combiner systems

Combiners (diplexers and multiplexers) are passive devices used to combine the power of two or more stations and feed the combined power to a common transmission line and/or antenna. Combiners may be used to multiplex multiple Hybrid IBOC signals or to combine analogue and digital signals for a hybrid signal. A multi-station combiner combines the power outputs of several radio stations into one composite antenna output. Combining is done to take advantage of a limited number of well-placed transmitting antennas. Combining also makes cost-effective use of expensive cavity-backed radiators and panel antennas that are desired for their ability to transmit with minimal tower-induced pattern distortion. Typically, the radio stations to be combined have carrier frequencies separated by a minimum of 800 kHz. This enables the possibility of lossless combining because the necessary frequency selective elements (e.g. filters) in this realm are practical to implement.

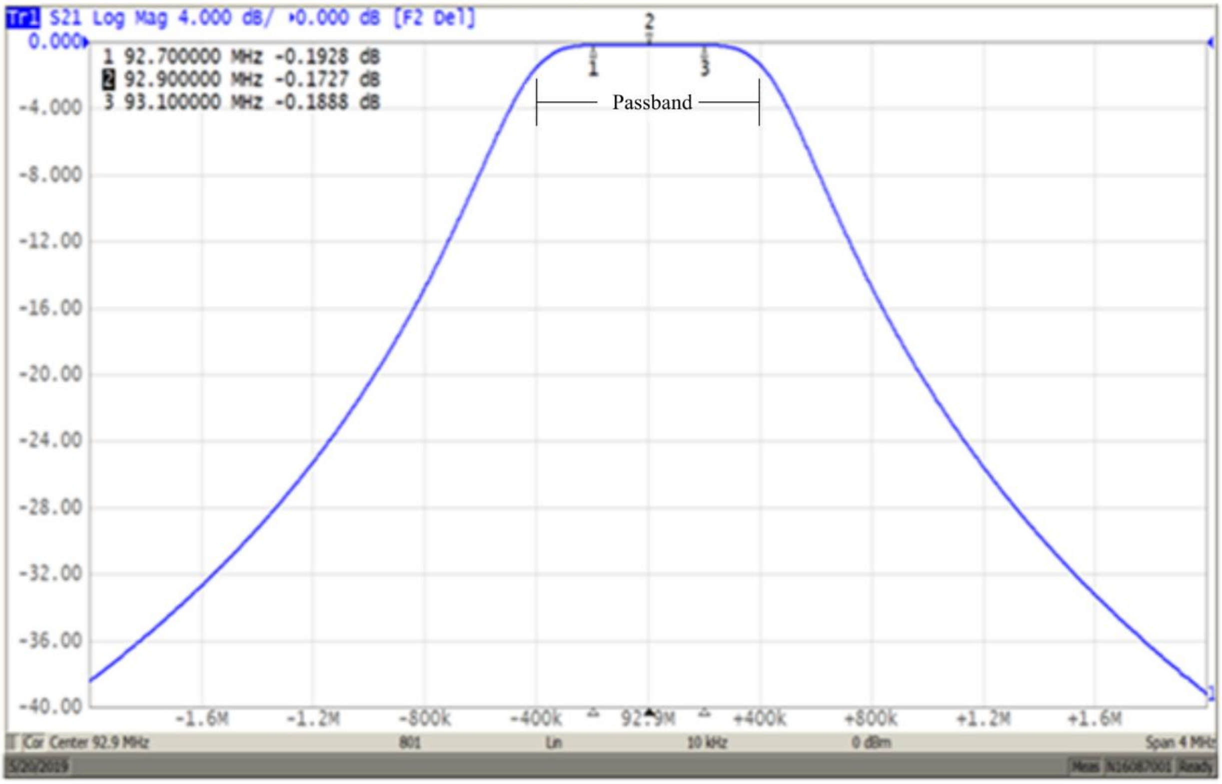
7.1 Filter characteristics

Spectral re-growth in RF amplifiers is a common concern when combining discrete signals such as the analogue and digital of a Hybrid IBOC transmission. In addition to precorrection at the low-level stages of the RF input, it may be necessary to filter the output of the high-power amplifier (HPA) to minimize out-of-band emissions and meet the signal-to-noise performance limits. These performance limits are covered in [3].

Typically, these filters are four-cavity or six-cavity elliptical designs with between 0.3 dB and 0.75 dB loss to the digital RF path. Due to the operating frequency and desired linearity, the filters require considerable space to accommodate installation. Band-pass filters (see Fig. 13), as their name suggests, pass a specific range of frequencies and attenuate signals outside of that range. This filter characteristic may be used to isolate desired signals from undesired signals.

FIGURE 13

Response of four-pole passband filter



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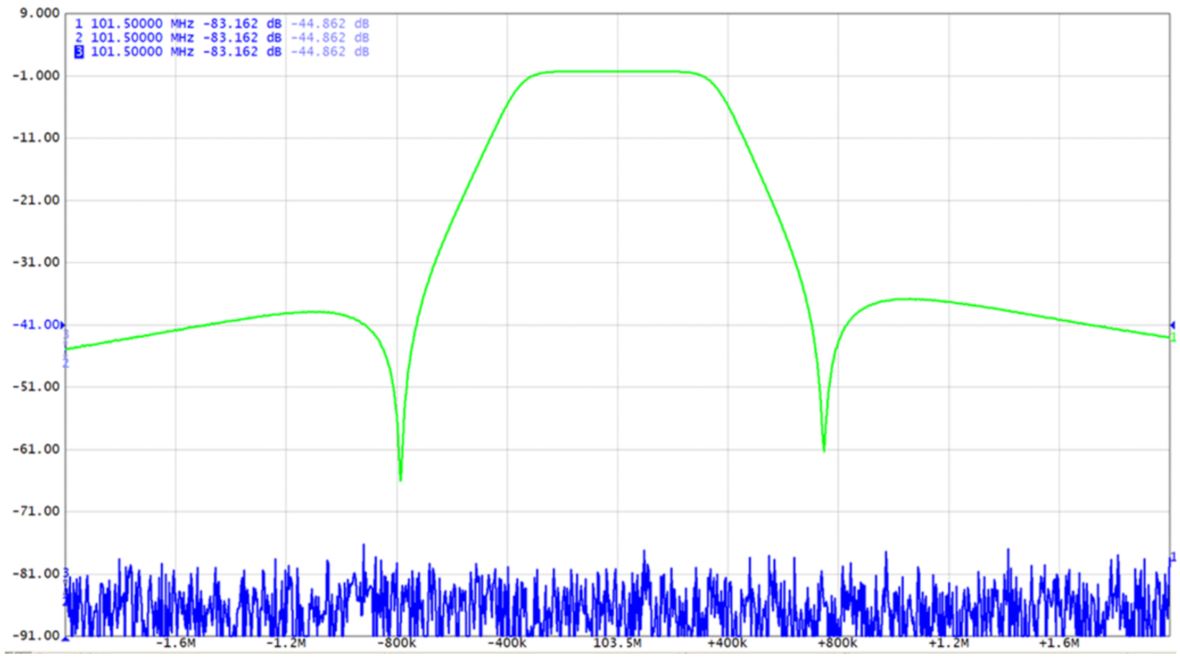
This additional suppression can also be provided by adding non-adjacent coupling to the band-pass filter. Adding non-adjacent coupling (a coaxial connection from the first cavity to the fourth cavity) to the band-pass filter adds a notch at the passband edges (see Fig. 14).

FIGURE 14

Passband filter with non-adjacent coupling



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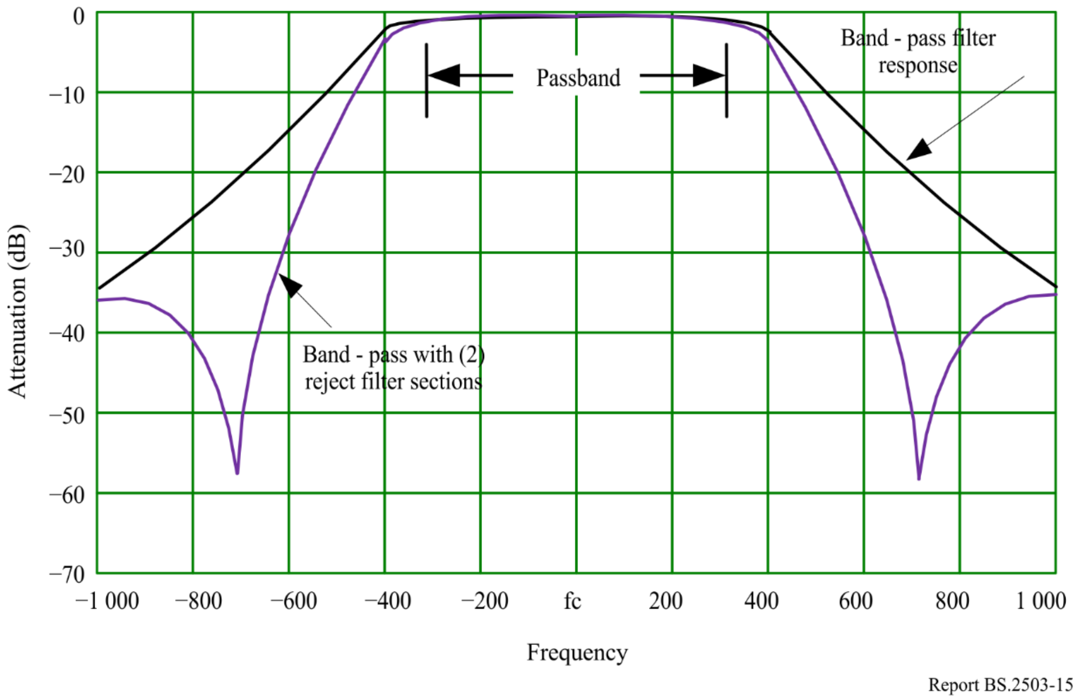
Additional isolation may be achieved by combining a band-pass filter with two reject filter sections to increase filter response (see Fig. 15) and provide additional unwanted signal attenuation.

Reject filters, also known as band-stop or notch filters, provide attenuation for unwanted signals (see Fig. 15). Reject filters are tuned to attenuate a relatively narrow range of frequencies while passing all others. Band-pass filters, reject filters, and hybrids form the basic building blocks of most modern combiner design. The various implementations are described in the following sections.

FIGURE 15

Band-pass filter with two reject filter sections



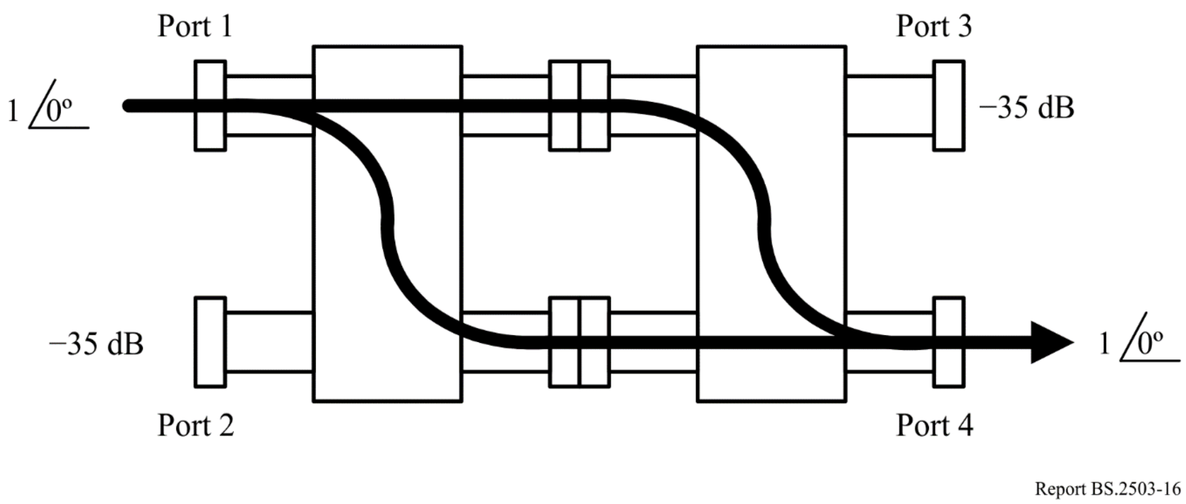
7.1.1 Balanced combiner

A 'Magic-T' or RF Hybrid is a 4-port 3 dB coupler that may be used to combine RF systems. The configuration allows energy in the E plane and H plane ports to be divided between the two colinear ports (on the same line): at the same time, the configuration isolates the E plane and H plane ports and the two colinear ports from each other. When RF energy circulates through the arm of the 'magic tee', signal reflections are created due to impedance mismatches at the junctions. This impedance mismatch results in power loss and limits how much power may be handled.

The balanced combiner is designed around two hybrids conjoined by the inner ports. This configuration is known as a Hybrid Ring or Rat Race Combiner (see Fig. 16). The Hybrid Ring balances the load and overcomes the power limitation of the Magic-T.

FIGURE 16

Hybrid ring combiner (Rat race combiner)



In a hybrid ring combiner, power flows diagonally from Port 1 to Port 4. Ports 2 and 3 are isolated by approximately 35 dB. If the hybrids are optimized for a specific operating frequency, up to 40 dB of isolation may be obtained. Two forms of combiners are popular:

– the notch filter combiner, and

– the band-pass filter combiner.

7.1.2 Notch filter constant impedance combiner

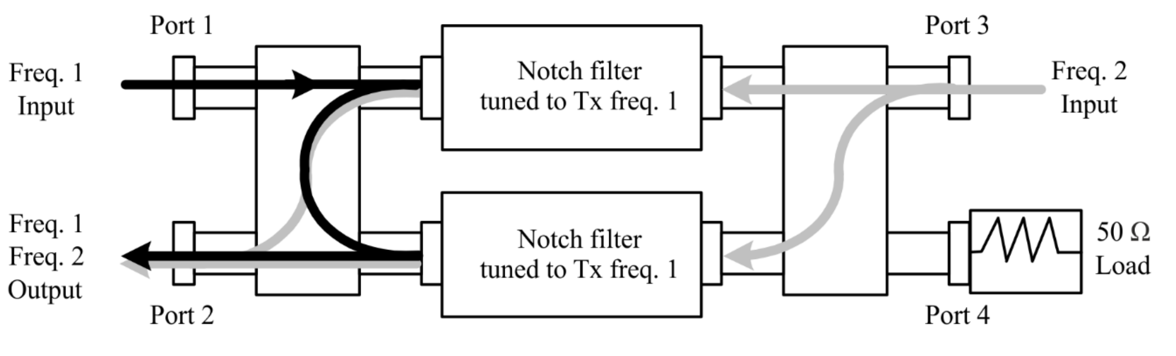
In the notch filter combiner, a notch filter is connected between the inner ports of the hybrid ring. Both notch filters are tuned to reflect transmitter frequency #1, which has been fed into Port 1. Frequency #1 reflects off both Notch filters and exits through Port 2. Transmitter frequency #2 enters through the broadband, Port 3, and passes through diagonally to exit from Port 2. Port 4 is terminated into the reject 50-ohm load (see Fig. 17).

Transmitter #2 is isolated from transmitter frequency #1 by 70 to 75 dB (the sum of the hybrid ring and notch filter isolation). Transmitter #1 is isolated from transmitter frequency #2 by only the hybrid ring: about 35 dB. Filters tuned to transmitter #2 frequency are required to minimize spurs generated by transmitter #1. The notch filter for transmitter frequency #2 is installed in line with the output of transmitter #1.

This grouping of hybrids and notch filters is known as module. Modules are added as the number of stations increases. Module #1's output (Port 2 on module #1) becomes the input to module #2 (Port 1 on module #2). Transmitter #3's input will require a notch filter for both transmitter #1's and transmitter # 2's frequencies.

FIGURE 17

Notch filter combiner



The main concern with a notch filter combiner is if the filters are not identically tuned to reject the same frequency range, an imbalance within the hybrid ring will occur, reducing isolation between transmitters and increasing the potential for spur generation in the transmitter.

The preferred method of rejecting multiple frequencies is to use a band-pass filter tuned to the frequency of operation. A single band-pass filter may be substituted for the multiple notch filters used at the transmitter #3 input.

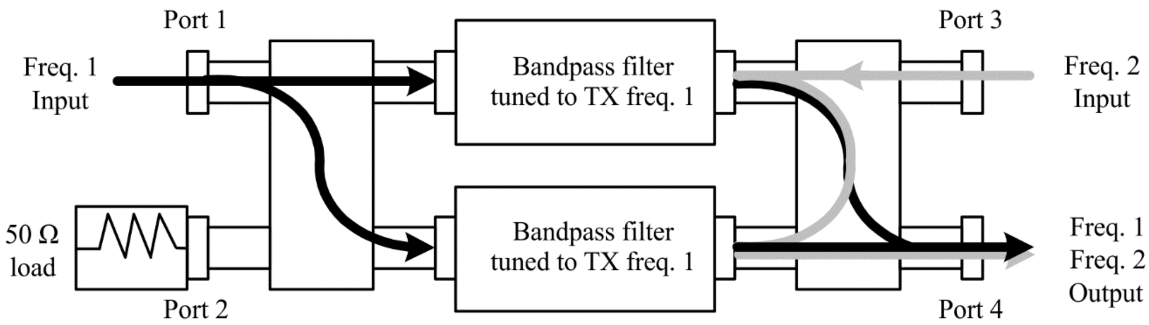
7.1.3 Band-pass constant impedance combiner

In band-pass balanced combining, band-pass filters are connected between the inner ports of the hybrid ring (see Fig. 18). Both band-pass filters are tuned to transmitter frequency #1. Transmitter #1 enters port 1 and passes through the band-pass filters and exits from port 4. Transmitter #2 enters at port 3 and is reflected by the band-pass filters tuned to transmitter#1's frequency and is reflected and exits from port 4 along with transmitter frequency #1.

Transmitter #1 isolation from transmitter frequency #2 is the sum of the hybrid ring and the isolation of the band-pass filter: about 60 dB. Isolation of transmitter #2 from transmitter frequency #1 however is only 35 dB and additional filtering must be added to transmitter #2's input port. This filtering could be either a band-pass or notch filter. Typically, modern combiners are built as a 'module' consisting of two hybrids and two filter sections. Additional filters may be added to improve the frequency response characteristic, but that improvement comes at the cost of increased group delay. Typically, the group delay limits of analogue stereo transmission supersede the group delay requirements for IBOC signal transmission.

FIGURE 18

Band-pass filter balanced combiner module



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A second module can be added to port 4 of module #1. Port 3 is then terminated with a reject 50-ohm load. This port may be used as an emergency input port for one of the stations. Transmitter #2 is then fed to port 1 of module #2. No input filter is required for transmitter #2 because of module #2's band-pass filter isolation. Transmitter #1's and #2's output appears at port 4 on module #2. In this manner, multi-station combiners may be assembled by feeding the output of each module to the broadband input of the next module (see Fig. 19). The practical limitation to the number of modules combined is constrained by the station channel spacing, insertion loss, and power rating for the line.

FIGURE 19

Typical VHF combiner configuration

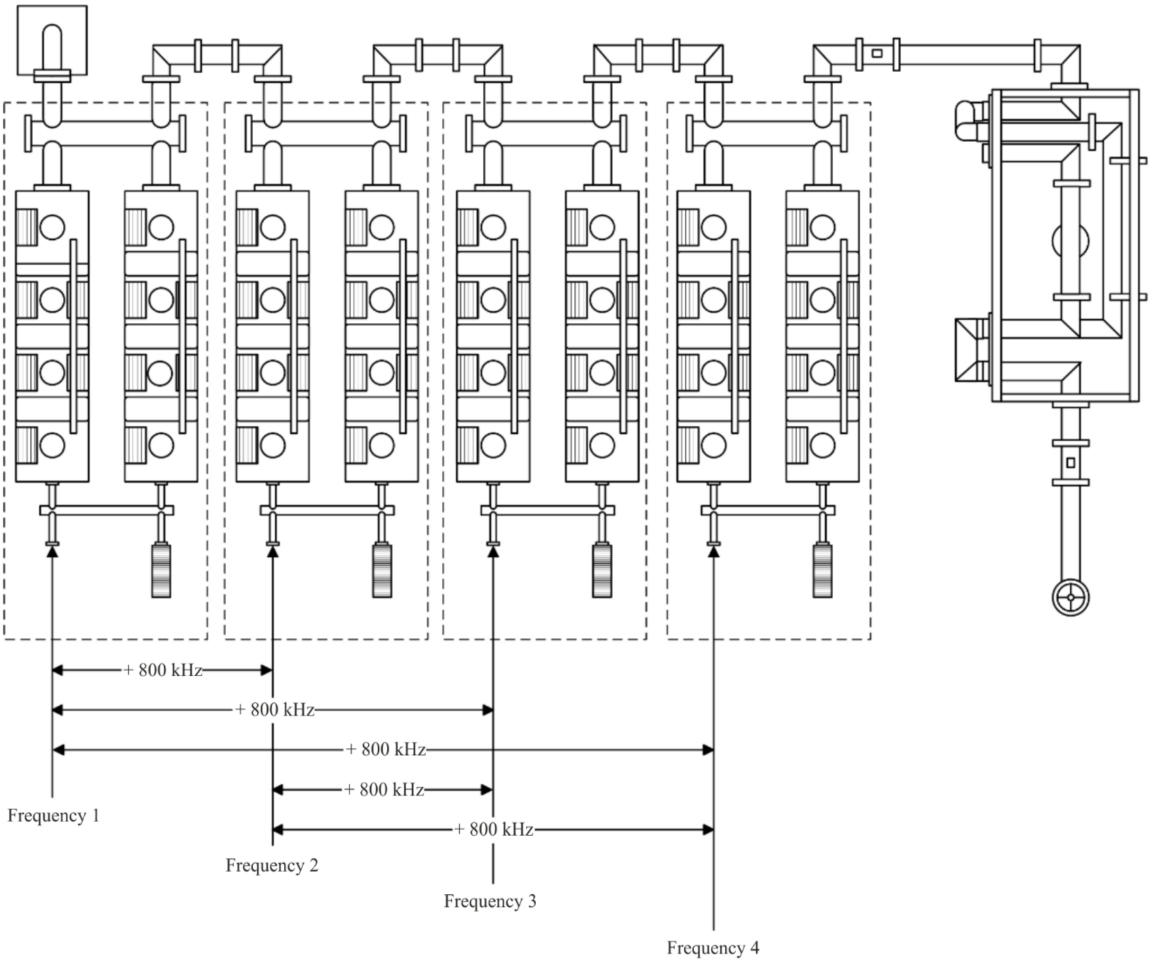

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FIGURE 20

Examples of match and insertion loss

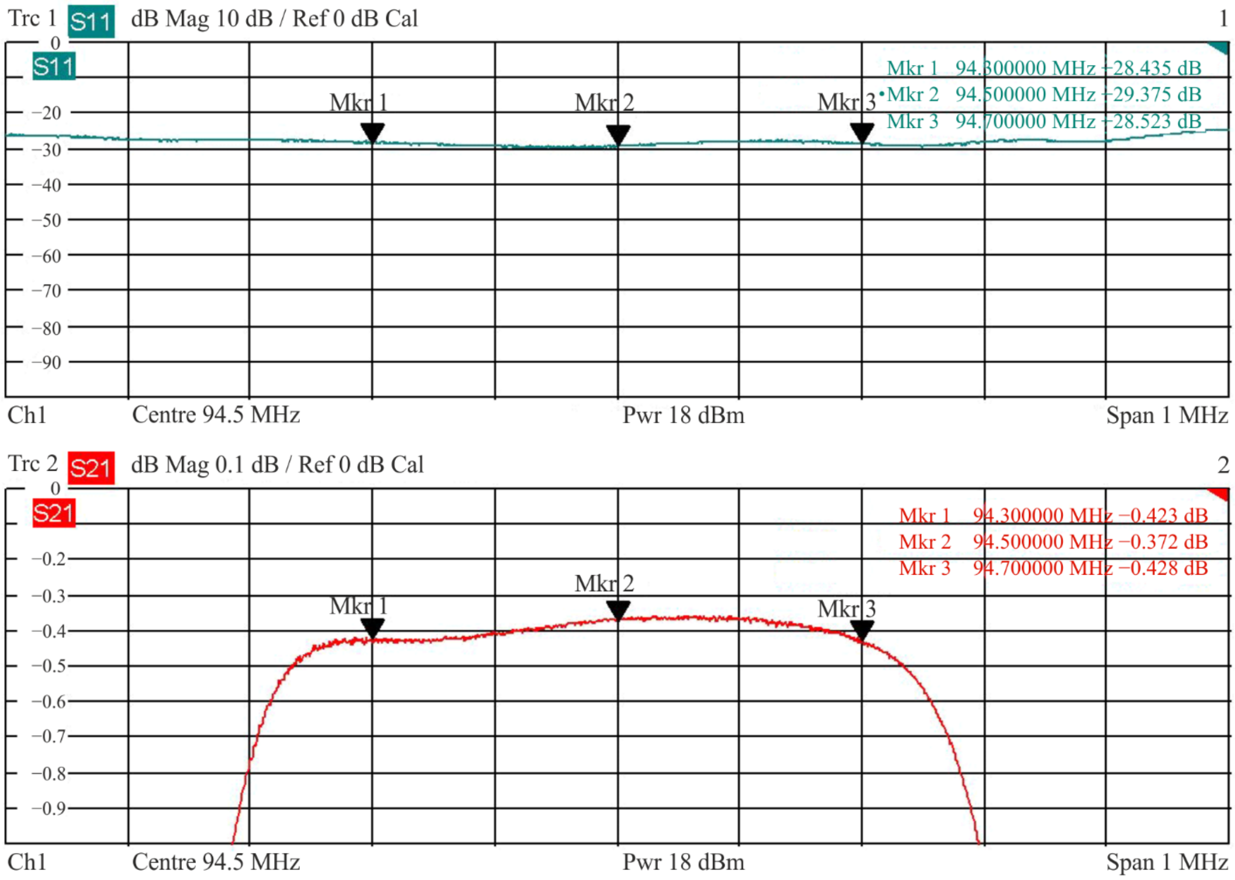

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FIGURE 21

Examples of group delay characteristics

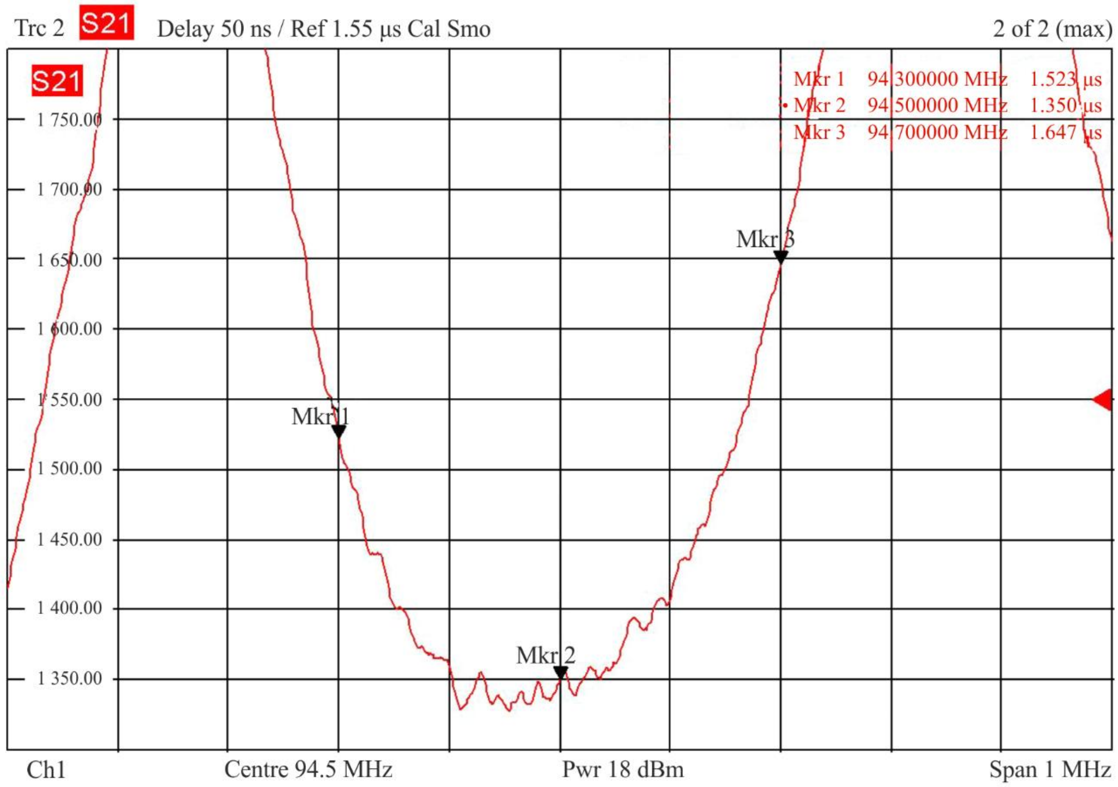

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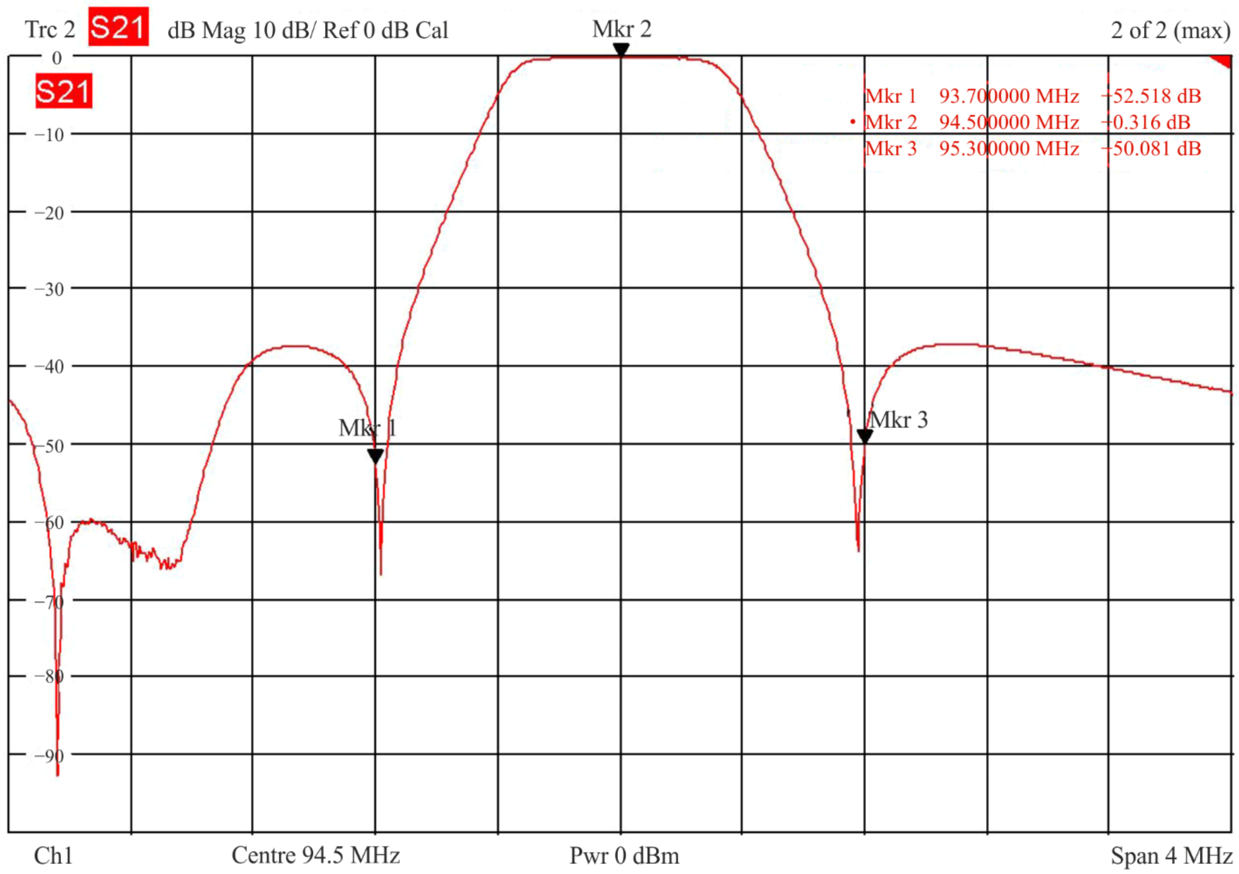
FIGURE 22

Measured Isolation (±800 kHz)



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8 Combined site facilities

Many multi-station sites are operational across the United States markets. These transmission facilities are privately operated and are not associated with any specific IBOC broadcast network. The following markets have combined digital and analogue transmission facilities:

- New York, NY
- Los Angeles, CA
- Chicago, IL
- San Francisco, CA
- Dallas-Ft Worth, TX
- Houston-Galveston, TX
- Washington DC
- Atlanta, GA
- Philadelphia, PA
- Boston, MA
- Miami-Fort Lauderdale-Hollywood, FL
- Seattle-Tacoma, WA

– Detroit, MI
– Phoenix, AZ
– Minneapolis-St. Paul, MN

The following sections provide details of combiner site facilities for three U.S. broadcast markets: Miami, Houston and New York City. Each site supports analogue and hybrid (simulcast) IBOC transmissions. The sites shown here are representative of similar IBOC Technology equipped combined facilities (with multiple vendors) in most US major markets. This site information provided here is for guidance on the feasibility of implantation. Any site implementation requires appropriate engineering analysis and design by an experienced industry expert.

8.1 Miami

The most extensive combined transmitter site in the Southeast US is located equidistant 20 km (12 mi) Southwest of Ft. Lauderdale and North of Miami in the city of Andover, FL. The Guy Gannett/441 Tower is one of the largest and highest power facilities of its kind in the United States of America.

In 2004, the site was upgraded with new RF combining hardware specifically designed to accommodate more stations and their digital transmission requirements. At the time, the state of the art in transmitter manufacturing required separate analogue and digital transmitters in order to achieve the power levels necessary to meet the 100 kW ERP class ‘C’ requirements. As such, a shared dual-input antenna was installed with separate transmission lines feeding ‘circular-right’ and ‘circular-left’ radiating elements through an antenna-mounted 3-dB hybrid combiner. The combining systems were also separate, with one set of hybrid/filter nodes for the analogue and one for the digital transmission. Ferrite circulators/isolators were also added to the digital path at each node to increase analogue/digital isolation.

As the state of the art in high power transmitter design improved, all but one of the stations elected to purchase transmitters that were capable of amplifying both the analogue and digital signals simultaneously (referred to as ‘common amplification’). These stations then only fed their allocated analogue port and did not use the digital port. In the spreadsheet below, all stations except WMIA use common amplification, feeding only the analogue port with the combined hybrid signal.

8.1.1 Miami site data

TABLE 4

Miami site data

Market	Miami, FL			Antenna information		
Tx Site:	American Tower LLC			Type:		Directional/Circular polarized
	390 Nw 210th Street (#75010)			Make/Model		ERI / COG1084-8CP-DA
	Miami / 33169, FL			HAAT		307 m (1007 ft.)
Latitude	25-58-03.3 N			AMSL		308 m (1010 ft.)
Longitude	80-12-33.2 W			HAG		306 m (1004 ft.)
Call Sign	Frequency	Power (kilowatts)				
		Analogue		Digital		
		TPO	ERP	Ratio (dBc)	TPO	ERP
WFEZ	93.1	17.48	100	−14	0.70	4.00
WMIA	**93.9**	**17.5**	**100**	**−20**	**0.21**	**1.00**
WZTU	94.9	17.5	100	−14	0.70	3.98
WPOW	96.5	17.19	100	−10	1.72	10.00

TABLE 5 (*end*)

WFLC	97.3	16.11	100	−14	0.64	4.00
WHYI	100.7	15.5	98	−14	0.60	4.00
WMXJ	102.7	15.86	100	−14	0.63	4.00
WMIB	103.5	14.5	100	−14	0.60	4.00
WHQT	105.1	15.92	100	v14	0.63	4.00
WAMR	107.5	13.74	95	??	??	??

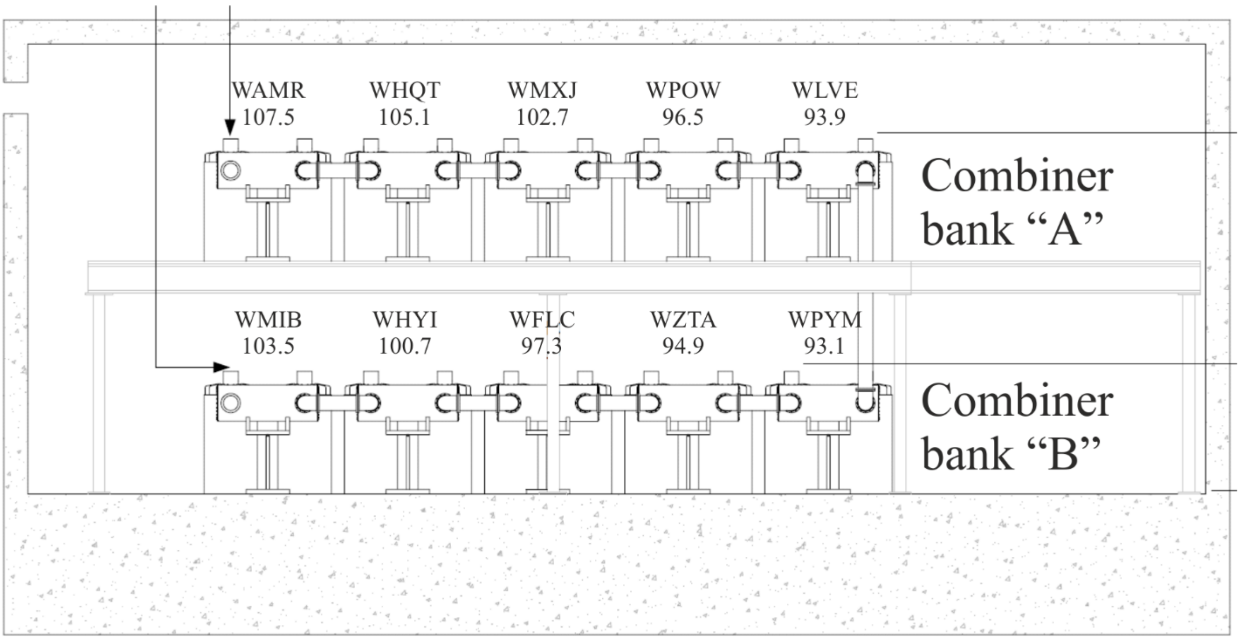
TABLE 4 characterizes the operating parameters of the stations operating into the Miami Gannett/441 Tower combiner/antenna. Only WMIA (in BOLD type) uses separate transmitters, combiners and feedlines for analogue and digital operation. The remainder use a single transmitter for "common-amplification" of the already combined Hybrid IBOC signal and only feed the analogue input port.

8.1.2 Miami physical plant configuration

Figures 23 and 24 show the analogue and digital hybrids, filters and interconnecting hardware that make up the Miami "Guy Gannett/441" combiner.

FIGURE 23

Diagram | Miami physical plant



Report BS.2503-23

FIGURE 24

Photo | Miami physical plant

Report BS.2503-24

Additional detailed information on the entire system is contained in an attached document from the antenna/combiner manufacturer, Electronics Research, Inc. – Complete IM report Miami FL.pdf.

8.2 Houston

The most extensive combined transmitter site in Houston, Texas, is located approximately 24 km (15 mi) Southwest of the city center. Often referred to as 'Senior Road', it is one of the largest and highest power facilities of its kind in the United States.

In 2011, the site was upgraded with new RF combining hardware specifically designed to accommodate more stations and their digital transmission requirements. At the time, the state of the art in transmitter manufacturing required separate analogue and digital transmitters in order to achieve the power levels necessary to meet the 100 kW ERP class 'C' requirements. As such, a shared dual-input antenna was installed with separate transmission lines feeding 'circular-right' and 'circular-left' radiating elements through an antenna-mounted 3-dB hybrid combiner. The combining systems were also separate, with one set of hybrid/filter nodes for the analogue and one for the digital transmission. Ferrite circulators/isolators were also added to the digital path at each node to increase analogue/digital isolation.

As the state of the art in high power transmitter design improved, some of the stations elected to purchase transmitters that were capable of amplifying both the analogue and digital signals simultaneously (referred to as 'common amplification'). These stations then only fed their allocated analogue port and did not use the digital port. In the spreadsheet below, all stations except KBXX, KODA, and KTBZ use common amplification feeding the combined hybrid signal the analogue port only.

8.2.1 Houston site data

TABLE 6

Houston site data

Market	Houston, TX			Antenna information		
Tx Site:	Senior Road			Type:		Omnidirectional/Circular polarized
	4110 Mchard (fm 2234) Road			Make/Model		ERI / COG3-20P-12
	Missouri City, TX			HAAT		585 m (1919 ft.)
Latitude	29-34-34.8 N			AMSL		605 m (1985 ft.)
Longitude	95-30-36.8 W			HAG		581 m (1906 ft.)
Call sign	Frequency	Power (kilowatts)				
		Analogue		Digital		
		TPO	ERP	Ratio (dBc)	TPO	ERP
KKBQ	92.9	22.5	100	-14	0.90	4.00
KTBZ	**94.5**	**22.5**	**100**	**-20**	**0.53**	**1.00**
KKHH	95.7	23	100	-14	1.08	4.00
KHMX	96.5	23.2	100	-14	1.08	4.00
KBXX	**97.9**	**22.5**	**100**	**-20**	**0.53**	**1.00**
KODA	**99.1**	**22.5**	**100**	**-20**	**0.53**	**1.00**
KILT	100.3	23	100	-14	1.08	4.00
KLOL	101.1	21.1	100	-14	0.96	4.00
KRBE	104.1	21.6	100	-14	0.86	4.00

TABLE 6 characterizes the operating parameters of the stations operating into the Houston “Senior Road” combiner/antenna. The three stations in BOLD type use separate transmitters, combiners and feedlines for analogue and digital operation. The remainder use a single transmitter for ‘common-amplification’ of the already combined Hybrid IBOC signal and only feed the analogue input port.

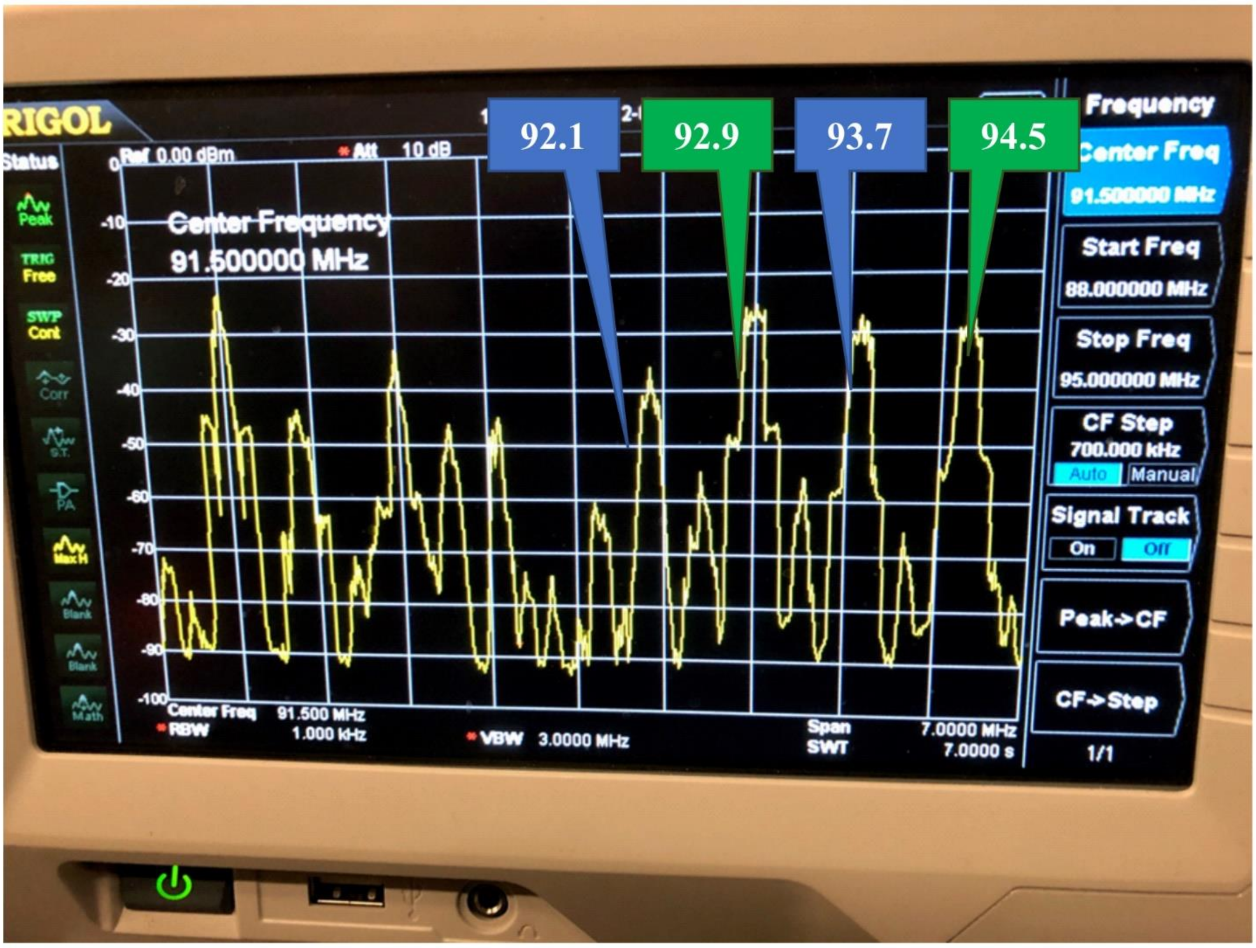
8.2.2 Houston spectrum analysis

The spectral shots that follow characterize the entire 88.1-107.9 MHz VHF-FM broadcast band in Houston, Texas. The spectrum analyser was connected to a high-quality off-air feed from a highly directional receive antenna located at the studio and pointed at the transmitter site. This receive configuration minimizes any potential multipath and provides a clean representation of the spectrum. However, as this is an off-air sample, other stations in the band are visible, along with any potential spurious artifacts that they might produce. It was impossible to obtain a spectral shot of a forward sample of the actual transmit antenna feed because of Covid-19 and time restrictions.

8.2.2.1 Houston spectrum 88 to 95 MHz

FIGURE 25

Houston market spectrum – Lower FM band



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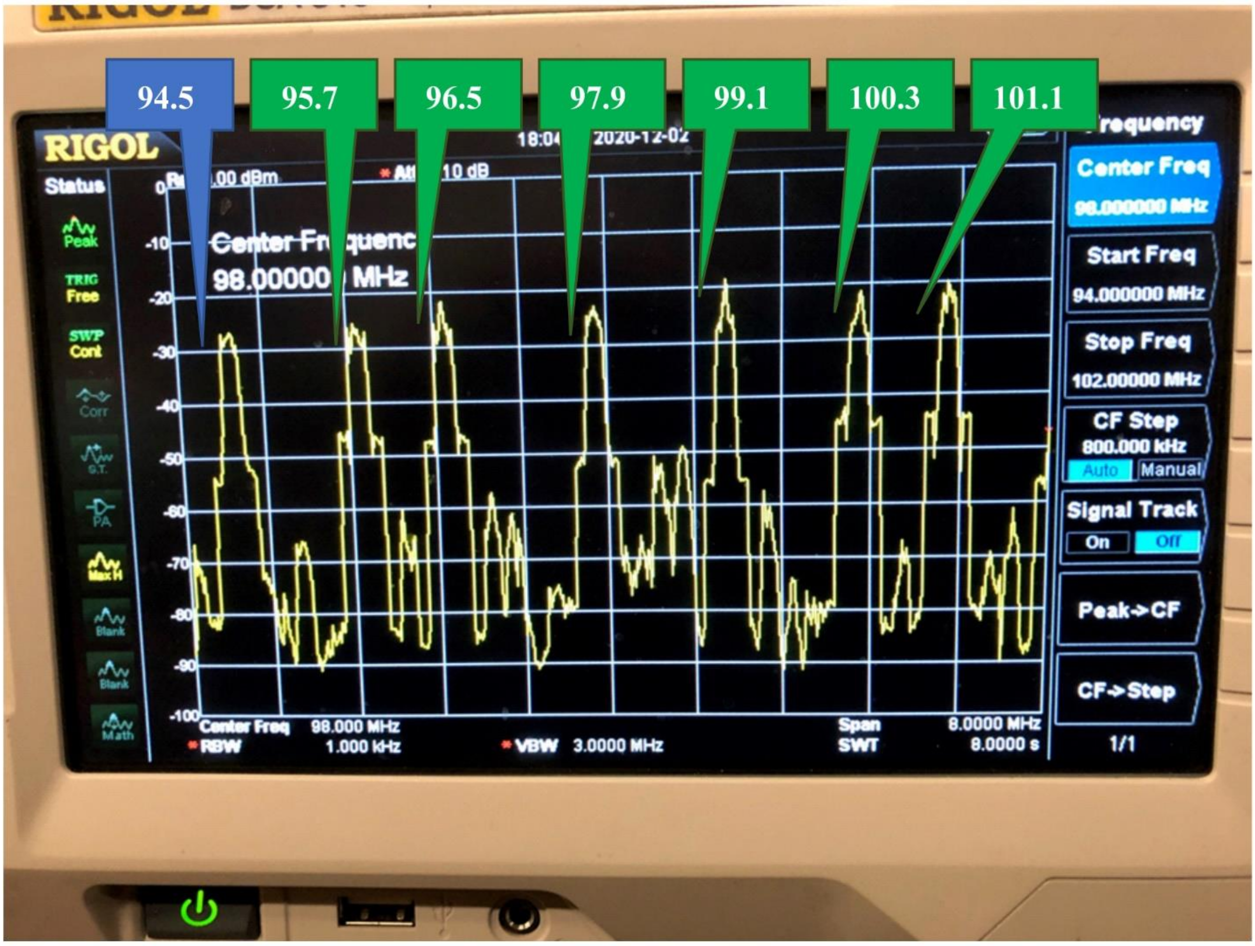
The spectrum analyser shot above characterizes the lower third of the 88-108 MHz FM broadcast band in Houston, Texas. “Senior Road” combiner stations are indicated with GREEN callouts.

8.2.2.2 Houston Spectrum 94 to 102 MHz

FIGURE 26

Houston market spectrum – Mid FM Band



Report BS.2503-26

The spectrum analyser shot above characterizes the center third of the 88-108 MHz FM broadcast band in Houston, Texas. “Senior Road” combiner stations are indicated with GREEN callouts.

8.2.2.3 Houston spectrum 101 to 109 MHz

FIGURE 27

Houston market spectrum – Upper FM band

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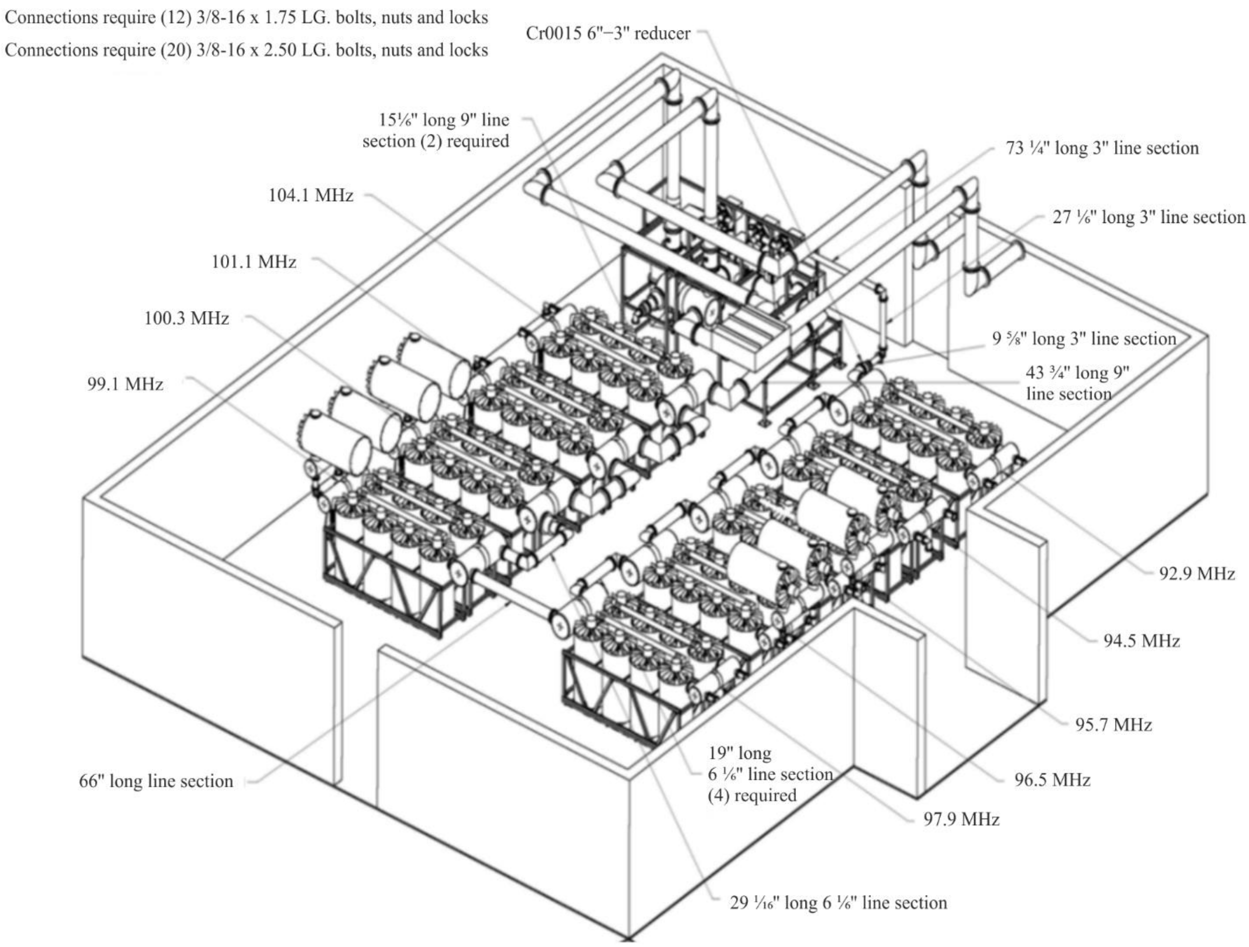
The spectrum analyser shot above characterizes the upper third of the 88-108 MHz FM broadcast band in Houston, Texas. The “Senior Road” combiner station is indicated with a GREEN callout.

8.2.3 Houston physical plant configuration

Figures 28 and 29 show the analogue and digital hybrids, filters and interconnecting hardware that make up the Houston “Senior Road” combiner.

FIGURE 28

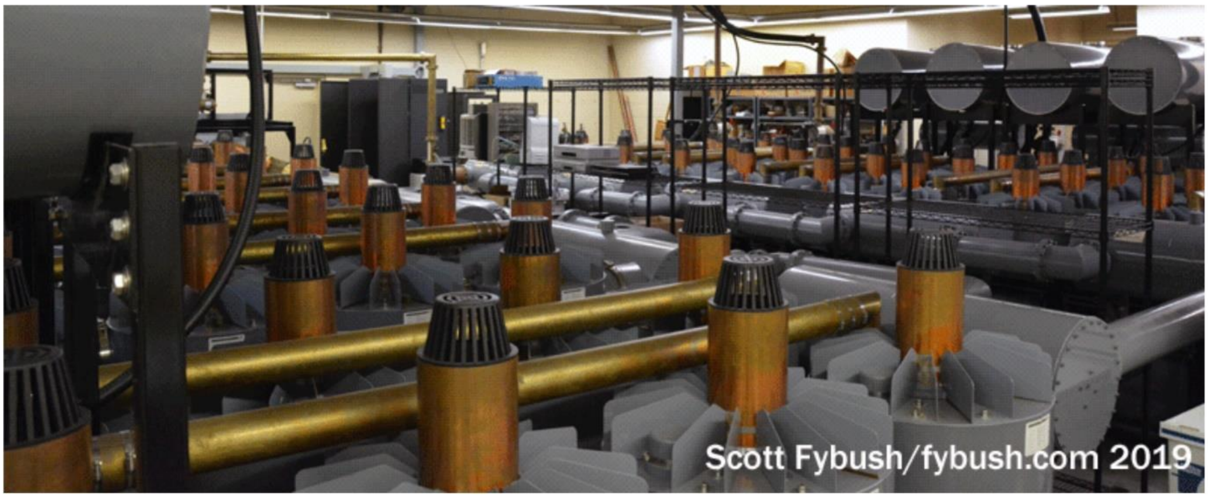
Diagram | Houston physical plant



Report BS.2503-28

FIGURE 29

Photo | Houston physical plant



Report BS.2503-29

Additional detailed information on the entire system is contained in an attached document from the antenna/combiner manufacturer, Electronics Research, Inc. – “Field Data Report 6-26-11.pdf”.

8.3 New York City

The most venerable VHF radio/tv transmission site in the United States is the Empire State Building in the heart of New York City. Experimental TV transmission began here just before Christmas, 1931 – only seven months after the skyscraper's construction. With the help of the National Broadcasting Company, Major Armstrong first tested Frequency Modulation from the structure's mooring mast in 1934. In 1965, the first VHF-FM combiner designed by Andrew Alfred allowed nine stations to share one common antenna, which used "slant" polarization, a precursor to modern circular polarization. In 2001, the Alfred combiner/antenna was replaced by a modern hybrid/filter combiner, allowing 12 stations to simultaneously operate into a new master antenna.

One of those stations, WNEW, 102.7 MHz, then became the first broadcast facility in the world to experimentally transmit IBOC technology on a multi-transmitter combiner. WNEW was also one of the stations used for field testing supervised by the National Radio Systems Committee (NRSC). Test reports were submitted to the Federal Communications Commission for the review of the digital broadcasting technology.

Fourteen (14) stations feed the ESB's 'master' combiner. Today 13 out of 14 stations are operating with IBOC Technology (except one, WFAN). This combiner provides only one port per station, so each transmitter combines the analogue and digital signals at low power prior to 'common-amplification'.

8.3.1 New York City Site Data

TABLE 7

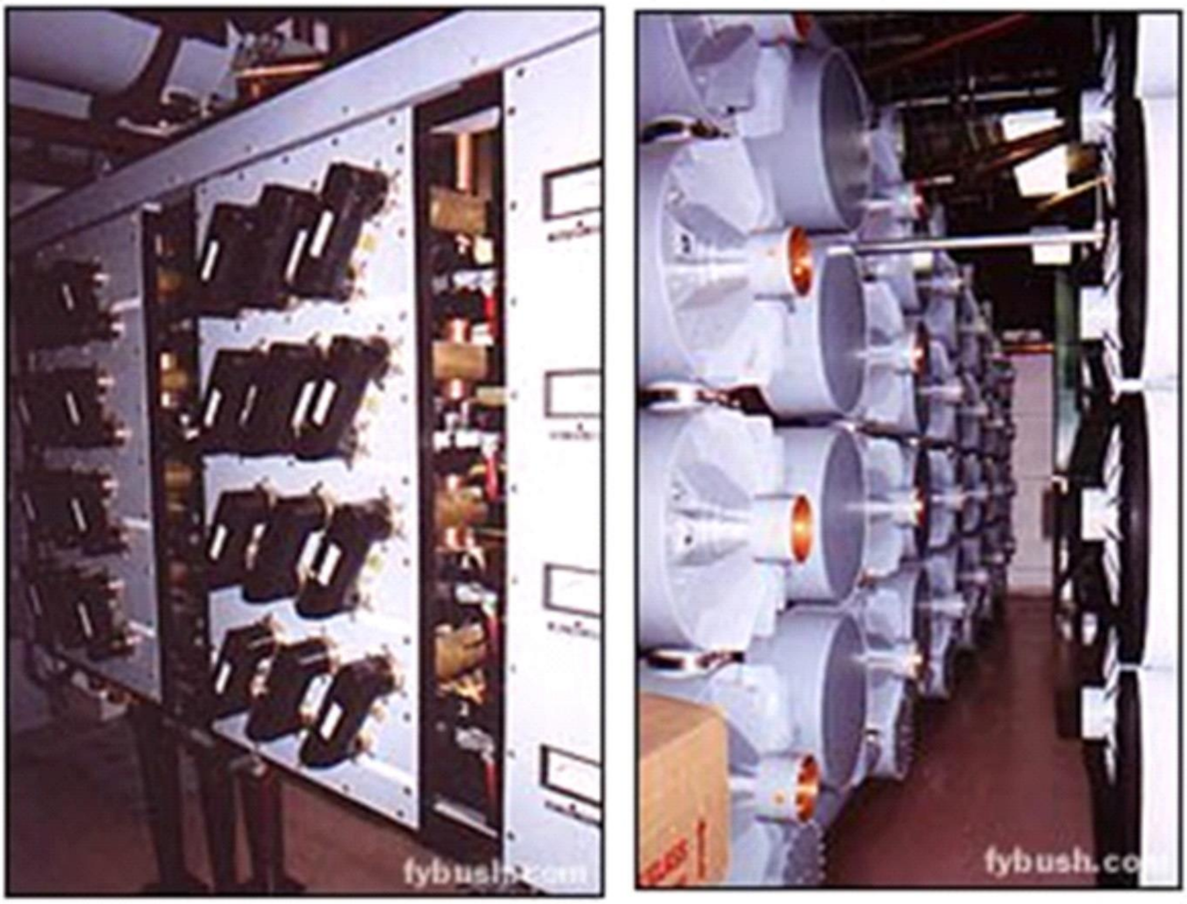
New York City site data

Market	NYC, NY			Antenna Information		
Tx Site:	Empire State Bldg.			Type:		Omnidirectional/Circular polarized
	350 Fifth Ave			Make/Model		Electronics Research Inc. / 1084-2-CP
	New York City, NY			HAAT		415 m (1362 ft.)
Latitude	40-44-54.4 N			AMSL		429 m (1407 ft.)
Longitude	73-59-08.5 W			HAG		413 m (1355 ft.)
Call Sign	Frequency	Power (kilowatts)				
		Analogue		Digital		
		TPO	ERP	Ratio (dBc)	TPO	ERP
WNYL	92.3	8.3	6	–14	0.32	0..23
WNYC	93.9	7.8	5.2	–14	0.31	0.21
WXNY	96.3		6	–14		0.24
WSKQ	97.9		6	–14		0.24
WEPN	98.7	8.7	6	–14	0.35	0.24
WHTZ	100.3	8.4	6	–14	0.33	0.24
WFAN	101.9	8.9	6	No HD		
WNEW	102.7	8.4	6	–14	0.33	0.24
WKTU	103.5	8.5	6	–14	0.34	0.24
WAXQ	104.3	8.4	6	–14	0.33	0.24
WWPR	105.1	8.4	6	–14	0.33	0.24
WQXR	105.9	0.78	0.61	–14	0.03	0.02
WLTW	106.7	8.7	6	–14	0.35	0.24
WBLS	107.5		4.2			

8.3.2 New York City physical plant configuration

FIGURE 30

Photo | New York City physical plant



Report BS.2503-30

References

[1] Xperi / iBiquity | Transmission Signal Quality Metrics for FM IBOC Signals | SY_TN_2646s

[2] National Radio Systems Committee | NRSC-5 RF Mask Compliance: Measurement Methods and Practice | NRSC-G201-B

[3] National Radio Systems Committee | IBOC Digital Radio Broadcasting Standard | NRSC-5-D

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