Breaking the Sound Barrier: How to Broadcast Digital Audio on Your FM Carrier

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Abstract. *We present the status of recent development work with an On-Carrier FM digital audio technology. A bandwidth efficient digital waveform has been tested which delivers up to 160 kilobits per second of usable data. The waveform occupies the subcarrier portion of an FM signal. We show how emerging digital technologies can be applied to produce an affordable and reliable new digital service on exsiting FM stations. Emerging digital technologies offer FM broadcasters new opportunities previously assumed impractical. One such opportunity is the transmission of high quality digital audio, multimedia, and extra high speed data services in the subcarrier portion of the FM signal. These on-carrier services, which comply with current FCC regulations regulations including 47 CFR part 73*[1] *, can achieve bandwidth efficiencies of 5 b/s/Hz using today's technology. Analog FM transmission remains intact while new broadcast services are simply plugged into existing broadcast exciters. Digital audio broadcasting directly on FM carriers is now a possibility. A variety of new digital services can be created for home, car, portable, and computer reception.*

Introduction

Emerging digital technologies offer FM broadcasters the capability to transmit a high quality, stereo digital audio signal in addition to their conventional stereo analog broadcast by using the the SCS subcarrier portion of the FM signal. This on-carrier use complies with FCC regulations embodied in 47 CFR part 73, and can provide digital services up to 160 kilobits per second (Kbps) without interference to the analog stereo signal. Up to 320 Kbps can be achieved by stations broadcasting in mono, using additional bandwidth normally taken by the stereo composite (L-R) signal. In addition to digital audio broadcasting, high speed data and Internet broadcasting are also feasible.

Using high speed digital transmission on the FM subcarrier, analog FM transmission can continue while the new digital services are transmitted simultaneously. Bandwidth efficiencies of 5 b/s/Hz and more are feasible using today's technology. Table 1 provides examples of how data transmission rates are tailored to specific applications.

Various digital signal processing technologies such as bandwidth efficient modulation, audio compression, error correction, and fading control techniques are the key to expanding the capacity of the SCS portion of the FM signal. By combining the benefits of these techniques, robust high speed digital signals can be transmitted and received on the FM carrier. Proven multipath mitigation techniques including forward error correction, symbol interleaving, pilot tone tracking and adaptive equalization are employed to ensure quality reception in difficult environments.

Bandwidth Efficient Modulation for On-Carrier DAB

TABLE 1. Possible Subcarrier Services as a Function of Data Rate.

Data Rate (Kb/s)	1.2 - 2.4	16-32	64-128	128-160	320+
Service Examples	• RBDS • Paging • Differential GPS	• ITS /IVHS • Fax • Financial data	• DAB (stereo, broadcast quality)	• DAB (stereo, CD quality)	• DAB (5-ch CD quality) • Multimedia

In the last quarter century, significant strides have been made in the field of audio frequency digital signal processing, in terms of improved waveforms and cheaper devices. This has enabled telephone modems using leased general switched telephone circuits to advance from 300 bits per second to 14,400 bits per second and beyond using a variety of different waveforms and equalization schemes.

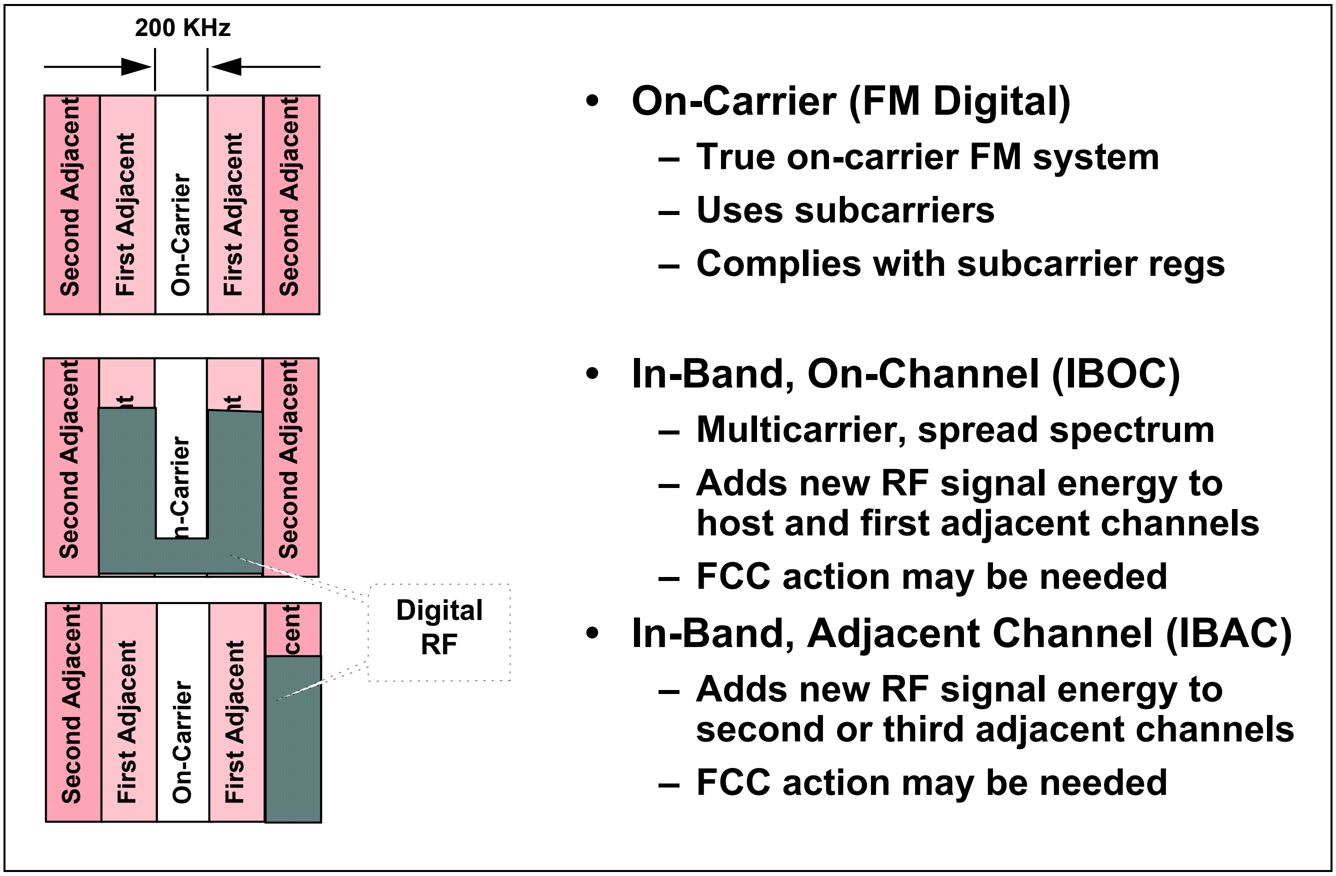


Figure 1. *An on-carrier method, using high speed subcarrier technology, can support DAB while maintaining full compliance with existing FCC regulations. Other proposed in-band DAB systems inject noise-like energy into adjacent channels. These so-called "saddlebags" caused interference with the main analog carrier, subcarriers, and other in-band DAB broadcasts .*

Just as digital signal processing (DSP) technology has increased the bandwidth efficiency of telephone modems, it is also advancing the digital audio broadcasting (DAB) state of the art. Today's audio baseband modulation schemes can support spectral efficiencies of 5-6 bits per second per Hertz (b/s/Hz) transmitted over an FM radio subcarrier. Advances in audio coding technology, developed by several manufacturers, make it possible to transmit broadcast- and CD-quality stereo signals using less than 160 Kbps of bandwidth (Table 1). The increasing popularity of CD players, CD-ROM and digital audio for multimedia PC's and games, and the introduction of HDTV with its high quality 2- and 5-channel digital audio, have all contributed to dramatically reduce the cost of sophisticated digital audio hardware. This makes affordable consumer FM DAB receivers possible within the next few years.

On-Carrier vs. In-Band On-Channel (IBOC)

An example of this rapid change in technology can be seen in waveform design for radio broadcast. When the designers of first-generation digital audio broadcast (DAB) systems contemplated transmission of "CD-quality" digital audio over the airwaves, it was not considered feasible then to obtain the requisite bandwidth (128-256 Kbps) necessary for DAB from on-carrier methods such as high speed subcarriers. Instead, first generation In Band DAB proponents devised techniques such as "In Band, On Channel" (IBOC) which employ signal modulations which are not "true FM", and inject noise-like energy into the licensed channel as well as adjacent channels (Figure 1). During laboratory tests sponsored jointly by the Electronics Industry Association (EIA) and the National Association of Broadcasters (NAB), proponent IBOC systems were found to cause audible interference to the analog FM signal, and were also found to interfere with subcarrier signals as well as adjacent-channel DAB signals[3]. Some systems also had difficulty when tested under simulated multipath conditions.

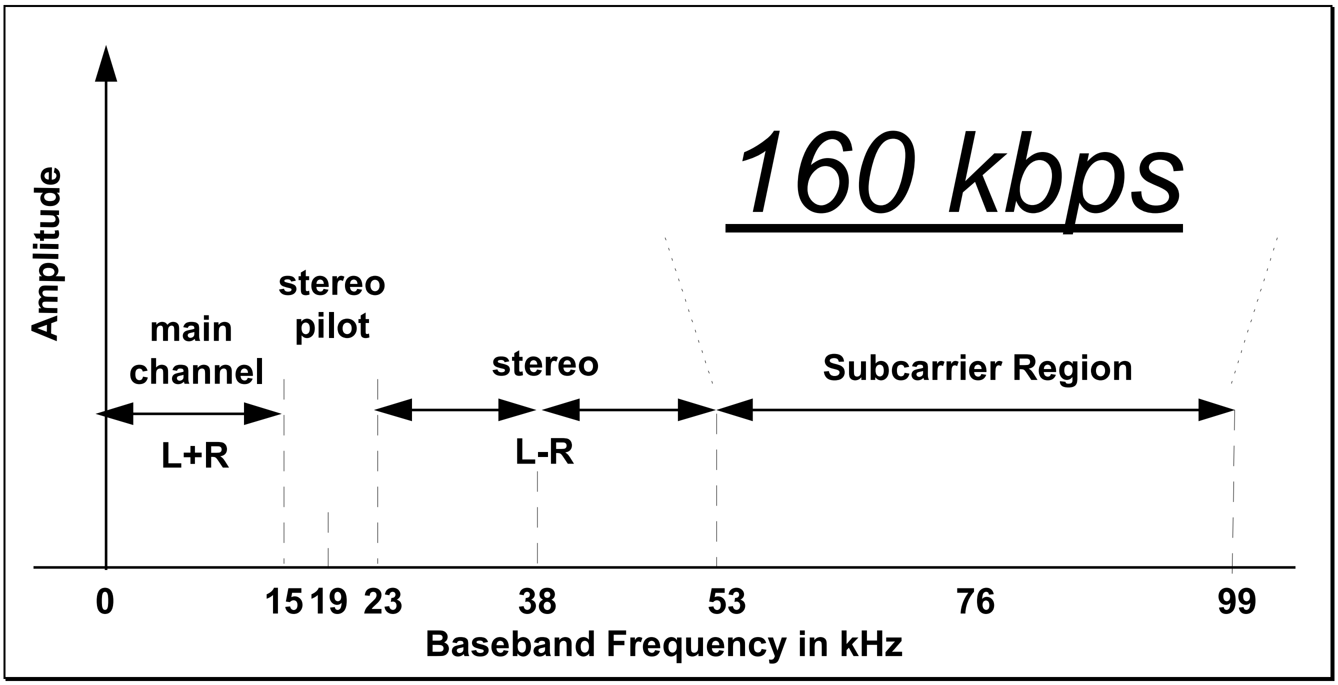


Figure 2. *Data rates of 160 Kbps are possible by transmitting signals with a bandwidth efficiency of 5-6 b/s/Hz over approximately 40 KHz of the subcarrier region, while maintaining analog stereo transmission. Signal injection (10%) is kept within the limits specified by 47 CFR part 73.319.*

Unlike IBOC and IBAC signals, high speed subcarrier technology is an on-carrier FM method, strictly complying with 47 CFR Part 73.319 (subcarrier) and Part 73.317 (RF mask) regulations. Maintaining signal injection within legal limits, high speed subcarriers with efficiencies of 5-6 bits/sec/Hz can be transmitted over 40 KHz of available bandwidth (57 KHz - 95 KHz) on carriers with stereo analog signals, achieving about 160 Kbps of channel data bandwidth (Figure 2). This is sufficient bandwidth to broadcast one stereo, CD-quality DAB signal[4,5]. Monaural stations, with 80 KHz of available bandwidth (19 KHz - 99 KHz), can transmit approximately 320 Kbps on their subcarriers (Figure 3). This is sufficient to broadcast compressed multimedia information (such as web site datacasting[6]) or even 5-channel digital "surround sound". In both cases, the FM subcarrier remains compatible with the analog signal, and conforms with all current regulations. A migration path to fully digital FM also exists. With regulatory approval, analog services can someday be phased out completely and replaced by a new digital signal.

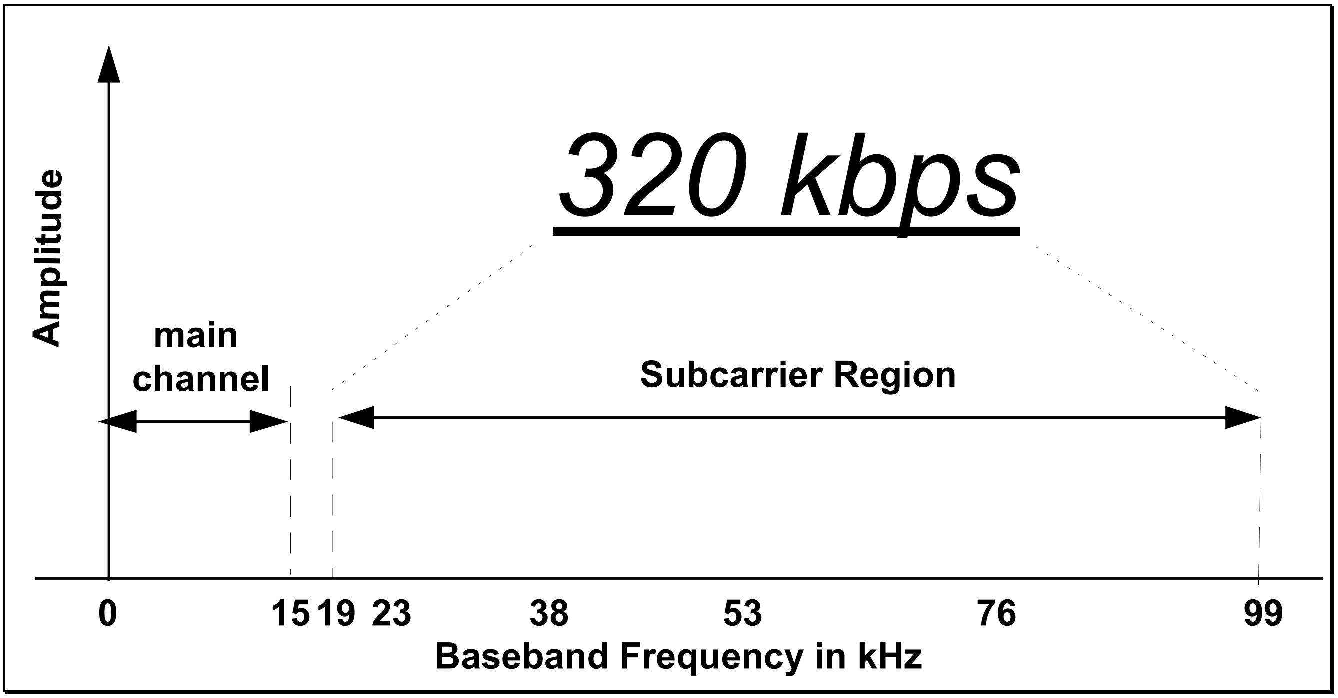


Figure 3. *Data rates of 320 Kbps are possible by transmitting over approximately 80 KHz of the subcarrier region This can be done while transmitting a monoaural analog signal. Note absence of the stereo pilot and L-R stereo composite in the diagram above.*

Over the Air Tests: Compatibility

A series of over the air engineering tests were conducted using the WCRB FM 102.5 transmitter in Needham MA during March and April, 1996. During these engineering tests, Sanders and WCRB engineers conducted: compatibility tests to determine the impact, if any, of the wide band subcarrier signal to WCRB's analog stereo signal; stationary reception tests at the 1 millivolt contour to measure data rate and bit error rate; and mobile testing within the city contour to determine the effect of multipath on the channel, using the basic modulation scheme with no interleaving or error correction.

The audio compatibility test results were excellent. Figure 4, below, shows a spectrum analyzer output of the WCRB baseband signal received in Hudson NH, forty miles from the transmit site. (Hudson is on the 1 millivolt contour for WCRB). -56 dBm was measured at the receiver inputs. The L+R, 19 Khz pilot, L-R stereo composite, and 38 Khz wideband subcarrier at 10% injection are all evident in the figure. There was no audible interference to the WCRB stereo signal, even when the injection was increased to the maximum (20%) permitted by 47 CFR part 73.319. Extensive tests conducted by WCRB and Sanders engineers revealed no audible or measurable interference to the analog audio which could be attributed to the wideband digital subcarrier.

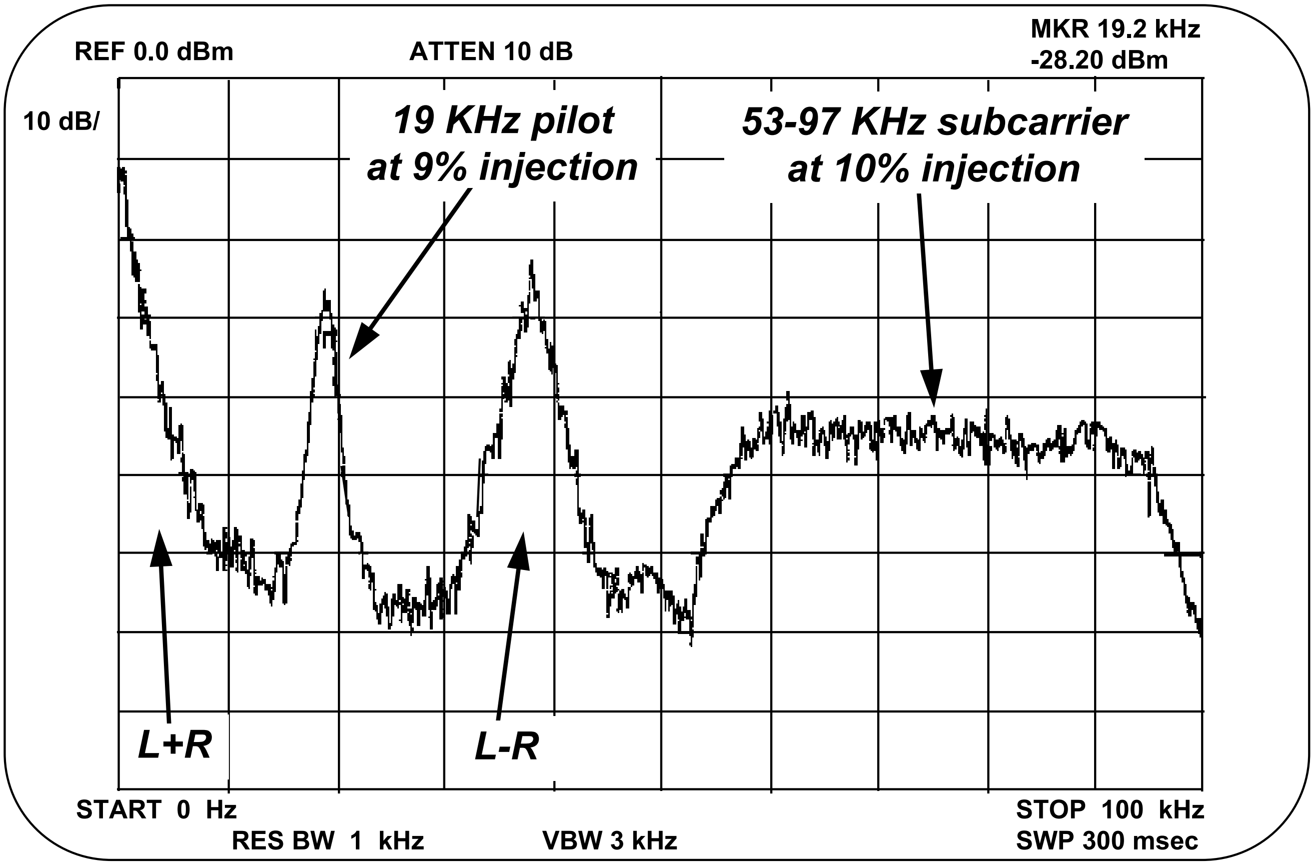


Figure 4. *Over the air testing has been conducted in cooperation with WCRB, FM 102.5 Boston, and KQOL, FM 105.5 Las Vegas. This spectrum analyzer image is WCRB's baseband signal recorded at its 1 millivolt contour in Hudson NH. The image shows the L+R, 19 Khz pilot, L-R stereo composite, and 160 Kbps wideband subcarrier.*

RF compatibility results have been excellent. Figure 5 shows the spectrum analyzer output of the WCRB RF signal with the wideband subcarrier, measured at the Hudson NH site. With the wideband subcarrier on, there was no change in WCRB's occupied bandwidth, in full compliance with 47 CFR part 73.317. The new wideband digital waveform occupies subcarrier spectrum currently used by conventional narrowband subcarriers. Services currently provided by those subcarriers can be accomodated more efficiently by the new wideband digital technology.

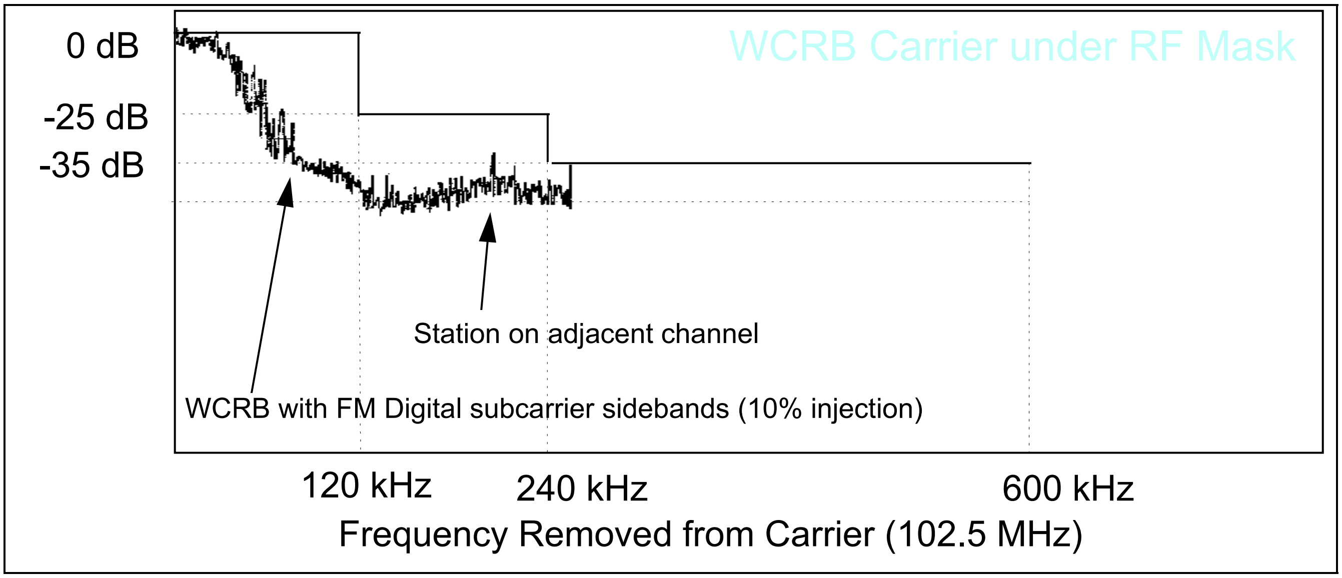


Figure 5. *Figure shows spectrum analyzer display of received RF signal of WCRB fully modulated with analog stereo and 160 Kbps wideband subcarrier. The RF mask specified by 47 CFR part 73.317 has been superimposed over the RF signal display. It is apparent that WCRB's signal with the wideband subcarrier is well within specification.*

Over the Air Tests: Data Performance

Stationary Data Tests: Two different data transmission rates (160 and 240 Kbps) were evaluated over the 40 mile path between WCRB's transmitter at Needham MA and Sander's receiver at Hudson NH. Performance in the stationary test was excellent, in spite of multipath evident on the analog audio. Error-free performance was achieved without the use of interleavers, error correction codes, or equalizers.

Another stationary test (and demonstration) was conducted during the 1996 Engineering Conference of the National Association of Broadcasters (NAB) at Las Vegas in April. During a continuous four-day period, the 160 Kbps wideband digital subcarrier was operated without receiver equalization, error correction or interleaving. Host transmitter was KQOL, FM 105.5, Boulder City NV. The receiver was located at the Las Vegas Convention Center about 18 miles away. The received signal was about 15 dB lower than the WCRB test. Considerable stationary multipath was evident in the received signal, resulting in uncorrected bit error rates of approximately 10^{-3} with burst errors typically 30 milliseconds or less in length.

These tests confirm the need for error correction coding in combination with interleaving. They also encourage the use of equalizers and antenna diversity for automotive applications. Consequently, error correction coding and short interleavers have been incorporated into the current design, dropping the delivered data rate from 240 Kbps uncorrected to 160 Kbps corrected.

Mobile Data Tests: A mobile test was also conducted along Route 9, a state highway connecting Needham with Boston. As with the stationary test, no equalization, error correction or interleaving was employed. Significant dropouts resulted from multipath and line of sight obstructions, verifying our laboratory multipath simulations which predicted deep fades (on the order of 50 dB). In reality, deep "stoplight fades" could last in excess of several seconds, well beyond the capacity of conventional "long" interleavers.

These results establish the need for new, robust methods of defeating extremely long "stoplight fades", a concern facing other IBOC proponents. Consequently, Sanders is proceeding on a novel method of beating the long stoplight fade. Unlike conventional interleaving, the new method will not result in long acquisition or re-acquisition times, making it practical for use in fast-tuning or scanning radio receivers.

Reception Range

Modern digital modulation schemes require less signal-to-noise ratio than analog while maintaining high levels of performance[7,8] (fewer than one wrong bit per million). Even at 10% injection, digital signals can provide good service at distances comparing favorably with the analog program (Figure 6). Simulations and over the air tests performed to date, including the Boston and Las Vegas tests earlier this year, validate this performance.

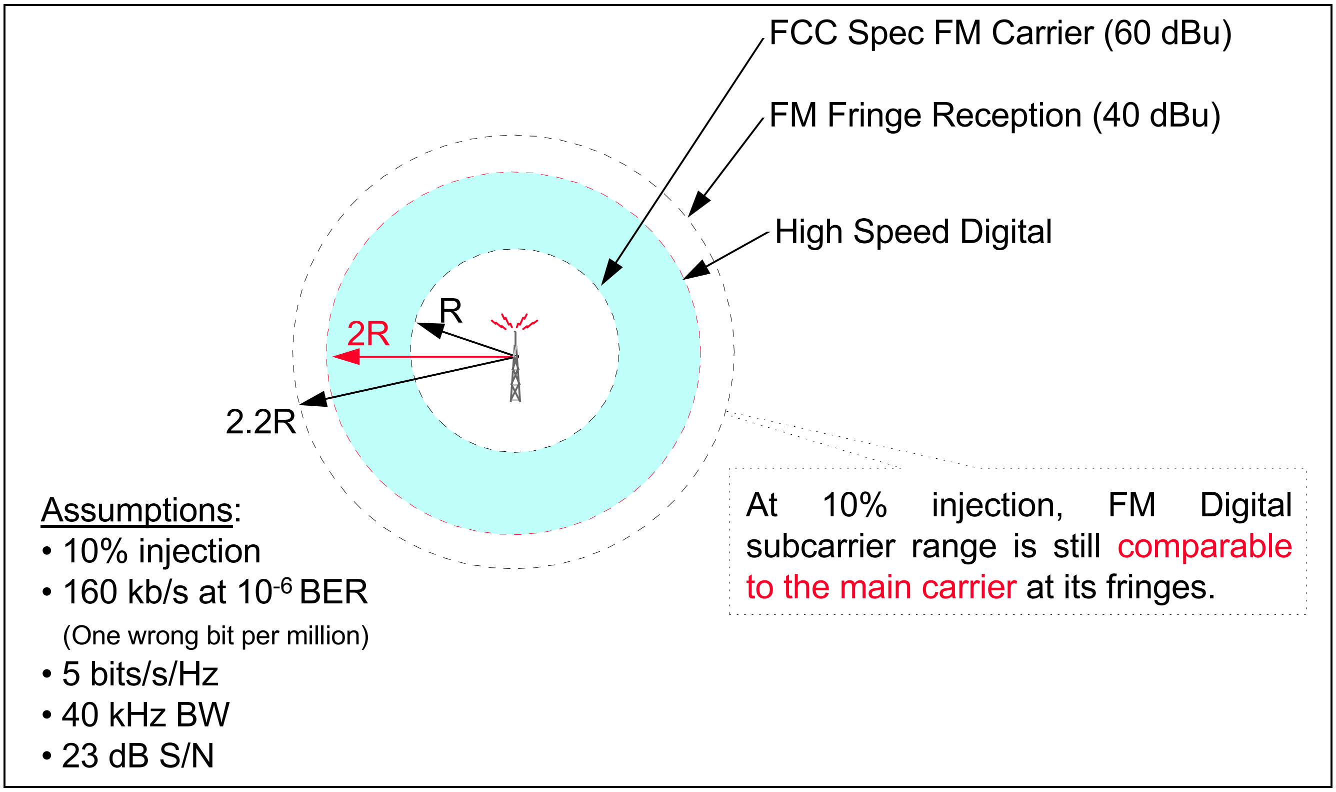
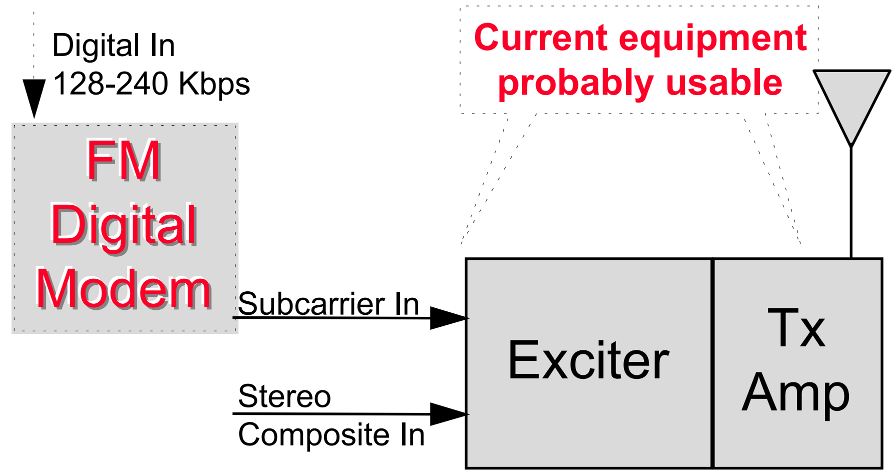


Figure 6. *A 160 Kbps high speed subcarrier signal, at 10% injection, can maintain quality digital service with 10^{-6} BER at distances comparing favorably with the analog signal at the 40 dBu fringe.*

Upgrading the Station

Upgrading the modern FM broadcast station for on-carrier digital FM is a straightforward operation. The key new element is a wideband digital subcarrier modulator (Figure 4). For stations broadcasting digital audio, a digital audio coder is also necessary to "compress" the bandwidth of an audio CD player (about 1.2 Mbps) to about 160 Kbps (a compression ratio of approximately 7.5:1) may be also be needed.



Patent Pending

Figure 7. *Upgrading the FM broadcast station for on-carrier FM DAB is straightforward, requiring the addition of a new wideband digital modulator. Unlike competing IBOC approaches, wideband subcarriers do not generally require a new transmitter and high-level combiner, offering a lower-cost implementation approach to the broadcaster. Wideband subcarriers have proven compatible with existing exciters and transmitters at commercial FM radio station such as WCRB FM Boston and KQOL Las Vegas.*

Consumer Receivers

Redesign of the consumer receiver for on-carrier digital FM is also straightforward. Two new components are required: the wideband subcarrier demodulator, and a digital audio decoder. Low cost chipsets are envisioned for installation in new digital consumer radios. These radios would only require slight modification from existing analog designs (Figure 8).

The FM discriminator output, used by the composite stereo demodulator, is also tapped as an input to the FM Digital demodulator. The demodulated digital data is decompressed by the digital audio coder, and converted back to high quality stereo audio by a digital to analog (D/A) converter. These components are inherently low-cost, because they are audio-frequency devices, like those found in telephone modems, CD players, and personal computer sound boards. Other DAB approaches require much faster digital chips, which drive up their cost substantially in comparison to the wideband subcarrier approach.

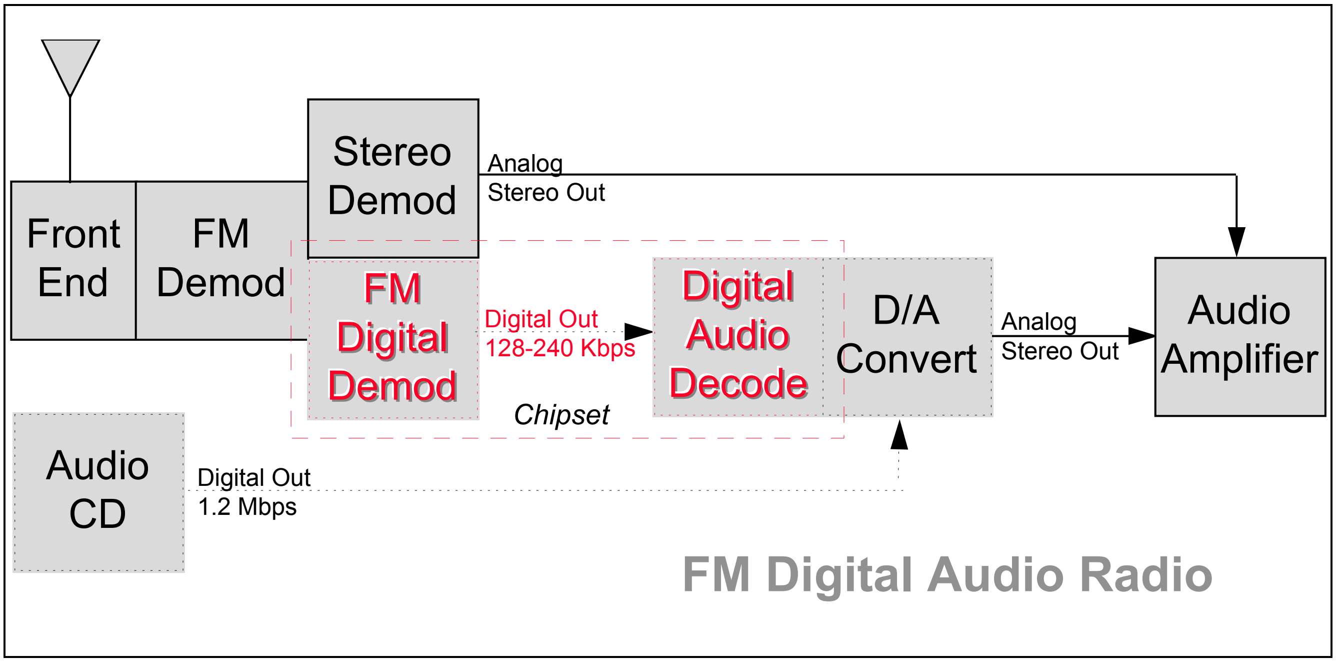


Figure 8. *Block diagram of a typical stereo system with FM Digital. Conversion of current consumer radio receivers to FM Digital operation is straightforward. A low cost chipset is planned.*

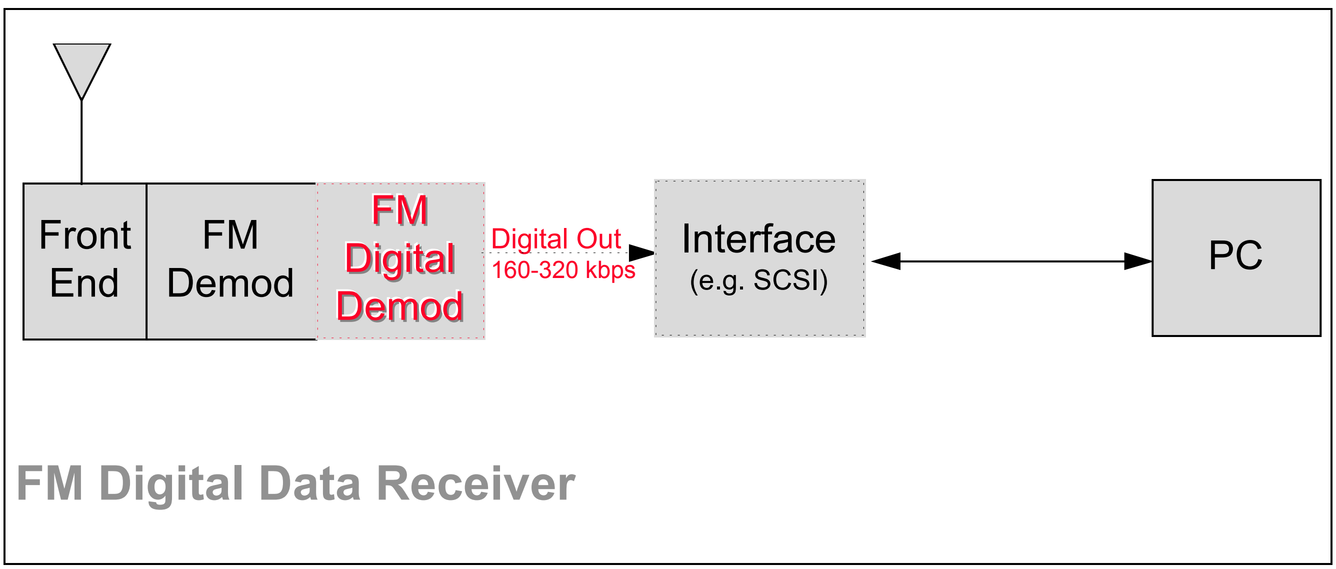


Figure 9. *Block diagram of a typical broadcast data receive modem using FM Digital chipset. Use of this technology, in combination with narrowband radio modems can unlock the potential of wireless web site datacasting.*

Internet Ready!

The same basic building blocks can be used to develop compact receive-only modems for personal computers (Figure 9). This will permit reception of high speed data broadcasts at 160-320 Kbps, either from traditional service providers, or from Internet web site datacasters. In combination with wireless digital PCS systems such as CDPD, mobile users can receive data downloads much faster than currently possible with conventional wireless

PCS systems. Such asymmetric delivery (high bandwidth download channel, low bandwith back channel) is ideal for wireless datacasting applications.

Summary

On-carrier DAB technology will soon offer the FM broadcaster a rapid and relatively inexpensive way to "go digital". Its high bandwidth efficiency, coupled with advances in digital audio coding, finally makes on-carrier digital audio possible. Decades of FM subcarrier broadcasting experience support new experimental evidence that on-carrier digital audio is fully compatible with existing analog stereo. Moreover, a market stimulus for DAB radios can be expected because of increasing penetration of high definition television (HDTV) and its 2- and 5-channel, CD quality digital audio. Wideband subcarrier technology will allow FM broadcasters to meet the demand for new digital services, without jeopardizing its existing base of listeners (Figure 10).

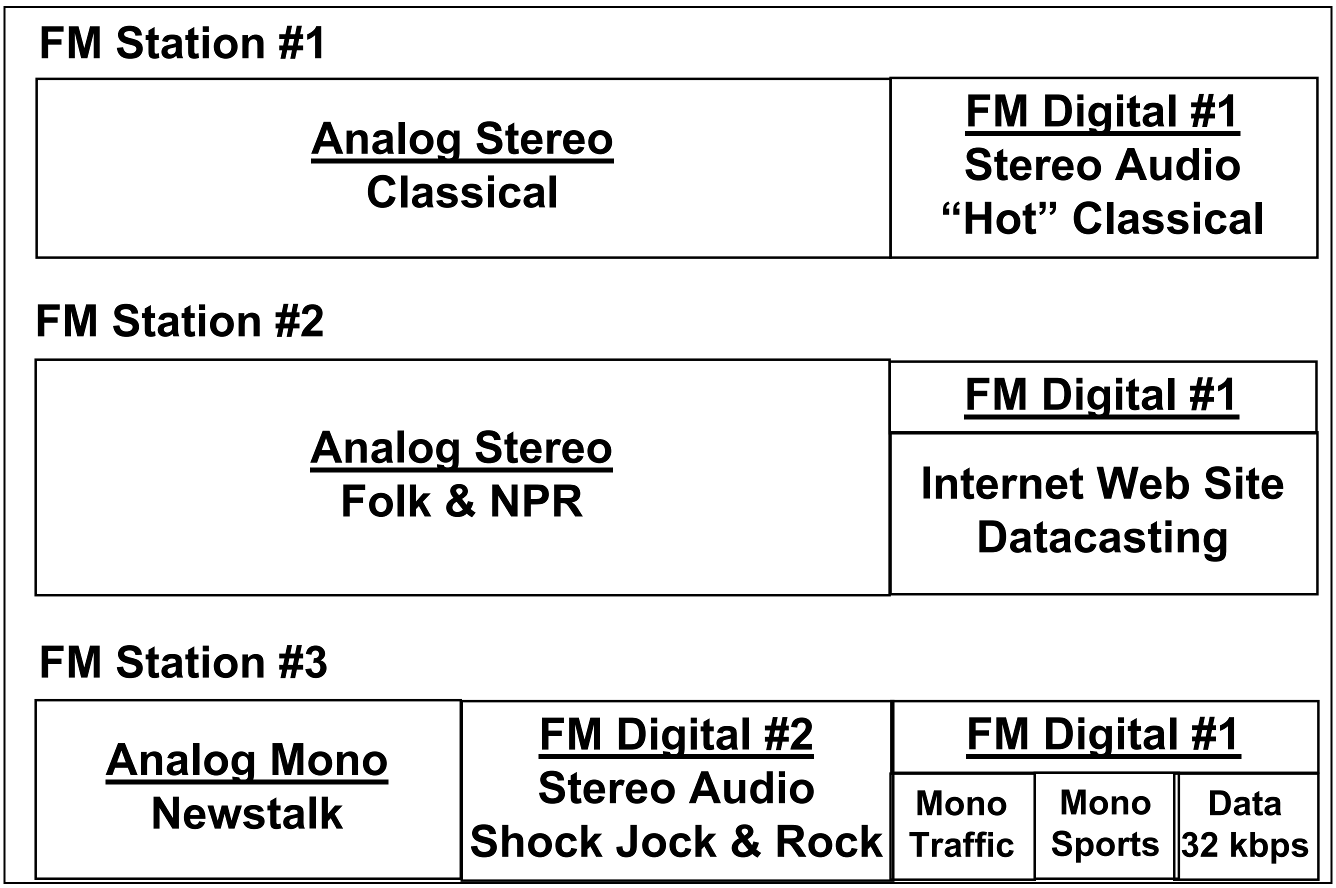


Figure 10. *The on-carrier FM DAB vision: two, or even three radio stations for the price of one! While keeping the analog stereo or mono format, the radio station can flexibly combine data and DAB services on their current subcarrier allocations.*

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